UNCLASSIFIED

Registration No.

22549

-Technical Report-

Durability Evaluation of the Effects of Fischer-Tropsch derived Synthetic Paraffinic Kerosene blended up to 50% with petroleum JP-8 on a Detroit Diesel/MTU 8V92TA Engine

December 2011

U.S. Army Tank Automotive Research, Development, and Engineering Center
Detroit Arsenal
Warren, Michigan 48397-5000

UNCLASSIFIED

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
19-12-2011	Final Technical Report	Apr 2010 – Dec 2011

4. TITLE AND SUBTITLE
Durability Evaluation of the Effects of Fischer-Tropsch derived Synthetic Paraffinic Kerosene blended up to 50% with petroleum JP-8 on a Detroit Diesel/MTU 8V92TA Engine

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Michael Claus / Eric Sattler / Nichole Hubble / Nick Johnson

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ground Vehicle Power and Mobility – GVPM TARDEC
Detroit Army Garrison – Michigan
6501 E. Eleven Mile Rd.
Warren, MI 48397-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
22549

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release; distribution is

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In order to characterize the effect of a blend of Jet-Propellant 8 (JP-8) and Fischer-Tropsch derived Synthetic Paraffinic Kerosene (FT SPK) on an 8V92TA MTU/Detroit Diesel engine, a 400 hour durability test, using a modified NATO protocol, was performed utilizing a 50% / 50% volumetric JP-8 and synthetic blend fuel. The results of this test were compared to a baseline engine running the same durability test in similar conditions utilizing neat JP-8 fuel. Analysis of test results and engine disassemblies did not show a significant degradation of fuel components. A damaged turbocharger due to instrumentation failure not related to the fuel source caused a decrease in power of the FT-SPK blend engine. Although the fuel blend did not result in a difference in fuel component wear when compared to neat JP-8, significant damage did occur from failed test equipment which affected the overall performance of the fuel blend engine. While JP-8/FT SPK fuel did not have a significant effect on engine components during this test, more testing is recommended to form a reliable conclusion on the effects of JP-8/FT-SPK blended fuel on the 8V92TA engine since one of the test engines was damaged during testing, the sample size was minimal and data was collected on two remanufactured engines.

15. SUBJECT TERMS
8V92TA, Fischer-Tropsch, Alternative Fuel, Blend JP8

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			M. Claus
Unclassified	Unclassified	Unclassified	SAR	51	**19b. TELEPHONE NUMBER** *(include area code)* 586.282.6793

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Acknowledgements

This NATO test was conducted at the U.S. Army's Detroit Arsenal and was part of a cooperative work effort between Tank Automotive Research Development and Engineering Center's (TARDEC) Ground Vehicle Power and Mobility (GVPM) and TARDEC's Fuels and Lubricants Technology Team (FLTT). The following government individuals were involved in this program:

Mr. Michael Claus: TARDEC GVPM, Test Engineer responsible for test setup, data reduction and analysis, customer interaction and authoring final report.

Mr. Andrew Brais: TARDEC, Assisted with initial set-up and trouble shooting of engine.

Mr. David Ostberg: TARDEC GVPM, Assisted with initial set-up and trouble shooting of engine.

Mr. Jeff Schmitz: TARDEC GVPM, Lead Engineering Technician responsible for test setup and test article operation.

Mr. Scott Mroz: TARDEC GVPM, Lead Electrical Technician responsible for data acquisition setup and test article operation.

Mr. Steve Roberts: TARDEC GVPM, Engineer, assisted with resolving instrumentation and software problems.

Dr. Pete Schihl: TARDEC GVPM, Senior Engineer, provided guidance and oversight with respect to data analysis.

Ms. Patsy Muzzell: TARDEC FLTT, Team Leader/Engineer responsible for program oversight and providing funding for this NATO test.

Mr. Eric Sattler: TARDEC FLTT, Engineer responsible for program oversight.

Mrs. Nichole Hubble: TARDEC FLTT, Engineer, assisted with data analysis and report.

Mr. Nicholas Johnson: TARDEC FLTT, Engineer, assisted with data analysis and report.

Table of Contents

Appendix

List of Figures

List of Tables

1.0 Introduction and Objective

The desire for sustainable, environmentally friendly automotive technologies continues to increase, as does the push for energy security. These efforts have resulted in the emergence of fuels derived from non-petroleum sources, or alternative fuels. Guided by US Army standards [1], the U.S. Tank Automotive Research, Development and Engineering Center (TARDEC) is assigned the responsibility of executing research, development, testing and evaluation (RDT&E) programs for ground vehicle fuels and lubricants. As the global fuel supply evolves to include alternative fuels, a TARDEC responsibility is to help the Army adjust to these changes by evaluating fuels to determine if they are suitable for use in Army ground tactical vehicles. The Army is chiefly concerned with alternatives to the primary fuel used by Department of Defense (DoD), which is jet propellant – 8 (JP-8). The specification for JP-8, MIL-DTL-83133G, does include specifications for Fischer-Tropsch (FT) derived Synthetic Paraffinic Kerosene (SPK) blended up to 50% with petroleum JP-8, though the approval to use these blends has not been fully implemented, pending further qualification/certification testing. This testing includes, but qualifications cannot be solely dependent on, the physiochemical properties of the fuel itself obtained from testing per the appropriate fuel specification. For example, specification testing may not indicate compatibility problems with materials used in fuel delivery systems, such as elastomers, metals, plastics, etc. Therefore, before these blends are qualified for use, they must undergo physiochemical testing, and in addition, as needed, either material, component, engine, and/or system testing to completely validate their suitability for use. TARDEC has already conducted many laboratory evaluations, including some component/engine evaluations, the results of which were published in the Society of Automotive Engineers peer-reviewed publications [2][3][4][5]. Continuation of the evaluation of alternative fuels for use in Army ground tactical vehicles will be advantageous to the military as the world fuel supply evolves to adopt alternative fuels and fuel blends helping to create increased national energy security.

The main objective of this test program is to measure the change in engine performance associated with the use of JP-8 vs. a 50/50 blend of JP-8 and FT SPK test fuels in the Detroit Diesel 8V92TA 500 hp diesel engine. In addition, any degradation in engine performance or potential component failures as endurance hours are accrued will be noted and analyzed independently for each fuel and fuel blend, namely JP-8 vs. the 50/50 blend. The specific objectives are the following:

1. To assess the performance and endurance of the currently-fielded Detroit Diesel 8V92TA 500 hp two-stroke diesel engine calibrated on DF-2 fuel by conducting full load performance baseline testing at standard North Atlantic Treaty Organization (NATO) Allied Engineering Publication-5 (AEP-5) conditions. Fuels used in this testing include Diesel Fuel #2 (DF-2), JP-8, and a 50% / 50% (v) blend of JP-8 and FT SPK.
2. Conduct a modified NATO AEP-5 400 hour Endurance Test protocol under normal conditions (described in Table 1) on two engines sequentially, one engine with JP-8 and a second engine with a 50/50 fuel blend of JP-8 and FT SPK fuels.

2.0 Conclusions and Recommendations

Data suggests that JP-8/FT SPK 50% / 50% (v) blended fuel did not have a significant effect on engine power compared with JP-8 fuel. Fuel flow rates throughout the tests stayed consistent for both engines, suggesting that JP-8/FT SPK fuel did not impose any additional wear on the fuel pump. During both the rated torque and rated power intervals of testing (Figure 1 and Figure 2), a significant power loss was measured in the JP-8/FT SPK-fueled engine, although this can be traced back to a damaged turbocharger whose damage was independent of any possible fuel issue. A temperature probe damaged the turbocharger of the JP-8/FT SPK engine after 140 hours of NATO cycle testing, decreasing the boost pressure by 2% (Appendix VII, Figure 26) and air mass flow into the engine by 3% (Appendix VII, Figure 31), although not enough data was collected to perform an accurate change in turbine efficiency calculation. There was a 3.8% power loss over the course of the 400 hour test for the JP-8/FT SPK engine throughout rated power and a 5.5% power loss during this period at rated torque. The JP-8 engine experienced a 0.6% power loss at rated power (Figure 3) and a 0.5% power loss at rated torque over 400 hours of testing (Figure 4).

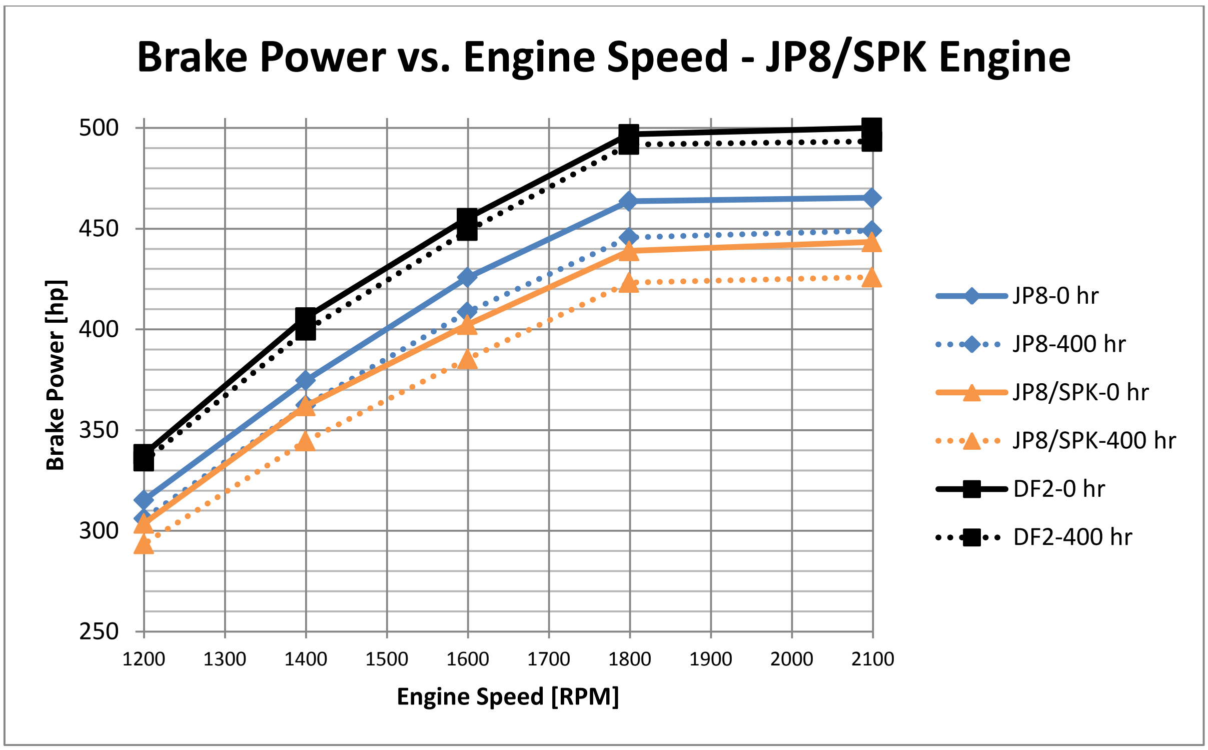

Figure 1. Graph of initial and final performance run on JP-8/FT SPK engine depicting horsepower vs. engine speed

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

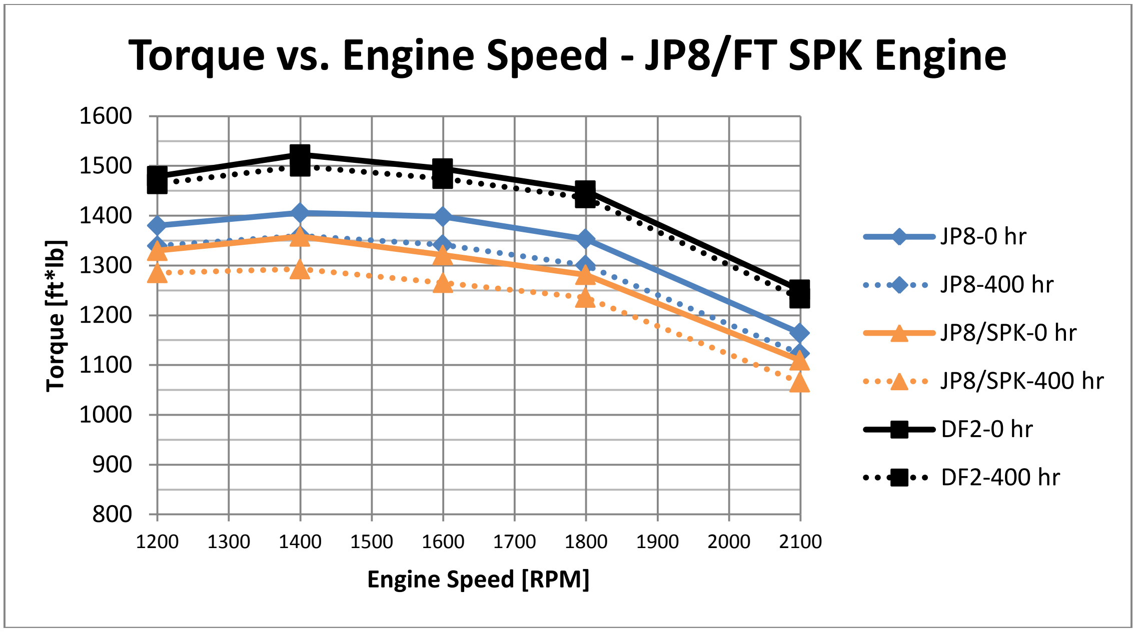

Figure 2. Graph of initial and final performance run of JP-8/FT SPK engine depicting torque vs. engine speed

For a given engine speed and given load, the JP-8/FT SPK 50%/50% (v) blend produced less power due to the lower mass density of the fuel when compared to JP-8 (see Table 6 and Table 7 in Appendix II). Since the fuel system and turbocharger of the 8V92TA were not tuned for this lower density blend fuel, this result was expected. Minor power loss in both engines over the duration of the test might be attributed to a build-up of fuel and oil deposits near the fuel injector tips, since detergents and dispersants are not present in JP-8 as they are in DF-2 fuel (see Figure 5 and Figure 6). Differences in initial power are the result of both engines obtained as rebuilt engines with different tolerance components.

Figure 1 compares brake power plotted against engine speed during the initial and final performance runs of the JP-8/FT SPK engine. This figure shows the power loss at the end of the 400 hour NATO cycle for all three fuels, although the DF-2 fuel had only a slight loss. Since the power decreased throughout the 400 hour durability cycle when measured on several fuels, the fuel is most likely not the direct cause and other factors may have contributed to the degradation throughout the 400 hour NATO test. During the disassembly process, it was discovered that the turbocharger was damaged on the turbine side, which would contribute to the power degradation of the engine. There was an average mass air flow decrease of about 3% from the 100 hour to the 200 hour full load power runs (see Appendix VII, Figure 31). This change of airflow decreased the air/fuel ratio, raising the exhaust temperatures of the engine (Appendix VII, Figure 27). Figure 7 shows the volumetric fuel flow rates versus the engine speed during the initial and final performance runs, which remain consistent.

The brake power change of the JP-8 engine was much less throughout the durability test. The synthetic blend fuel was not available to run full load performance tests during the 0, 100, 200 and 300 hour performance runs so two DF-2 performance tests were run during the 0 hour performance test. The initial DF-2 performance runs shown in Figures 3, 4 and 8 portray the variance an engine can have running two consecutive tests (one day apart) on the same fuel. As can be seen in the JP-8 fuel flow rate (Figure 8) and JP-8 brake power measurement (Figure 3 and Figure 4), both the fuel flow rate and brake power are about the same between the initial and final performance runs (within 3% error on fuel measurement).

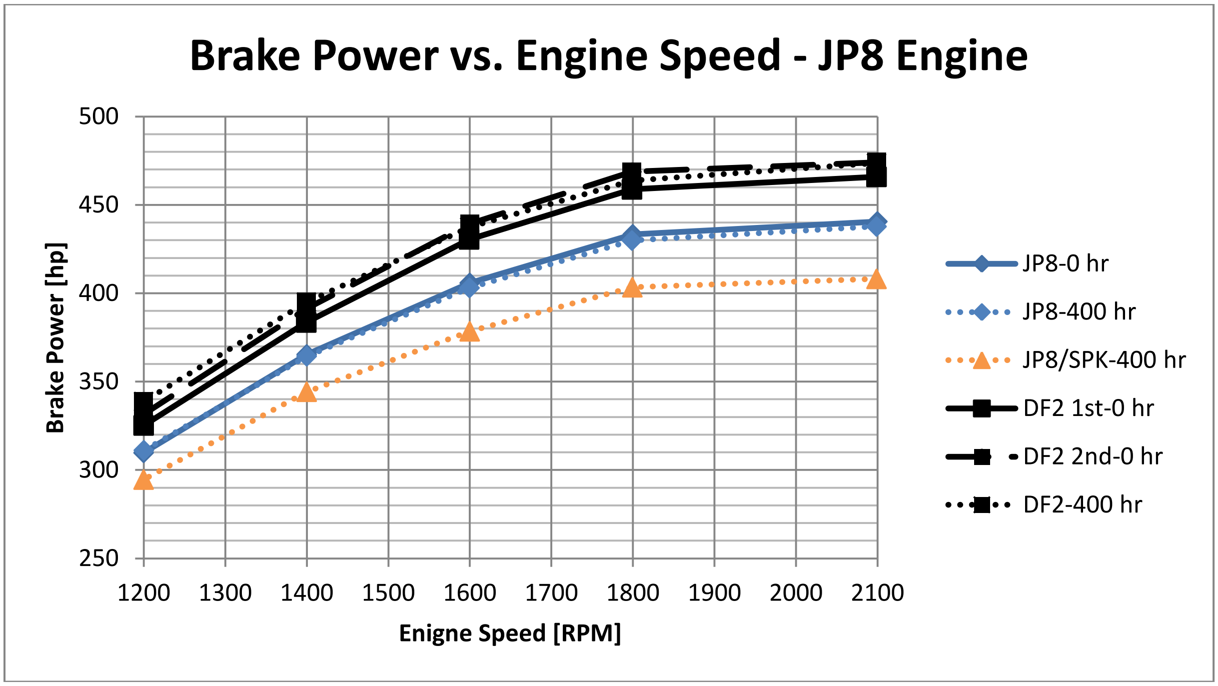

Figure 3. Graph of initial and final performance run on JP-8 engine depicting horsepower vs. engine speed

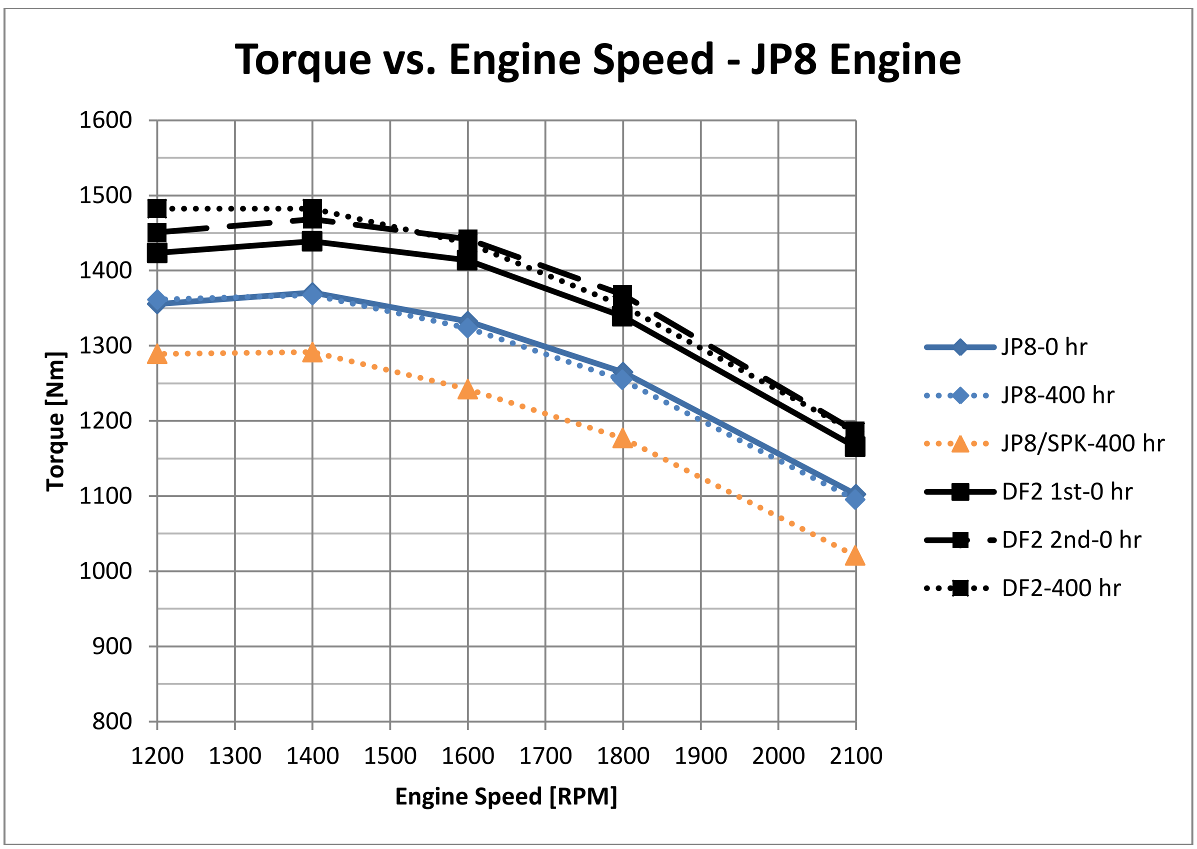

Figure 4. Graph comparing initial and final performance runs on JP-8 engine, depicting torque vs. engine speed

Figure 5. JP-8/FT SPK engine fuel injector with excess oil and fuel deposits after 300 hours of NATO testing

Figure 6. JP-8 engine fuel injector with excess oil and fuel deposits after 200 hours of NATO testing

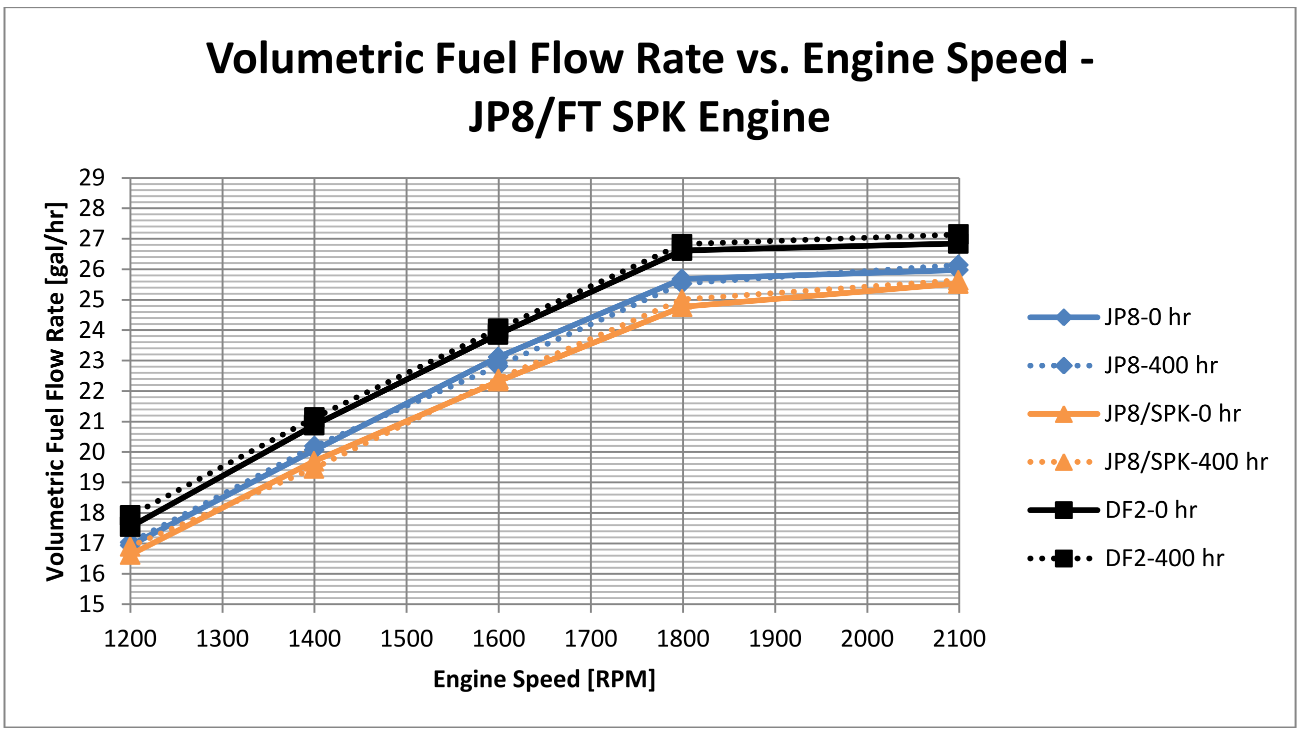

Figure 7. Graph of initial and final performance run of JP-8/FT SPK engine depicting volumetric fuel flow rate vs. engine speed

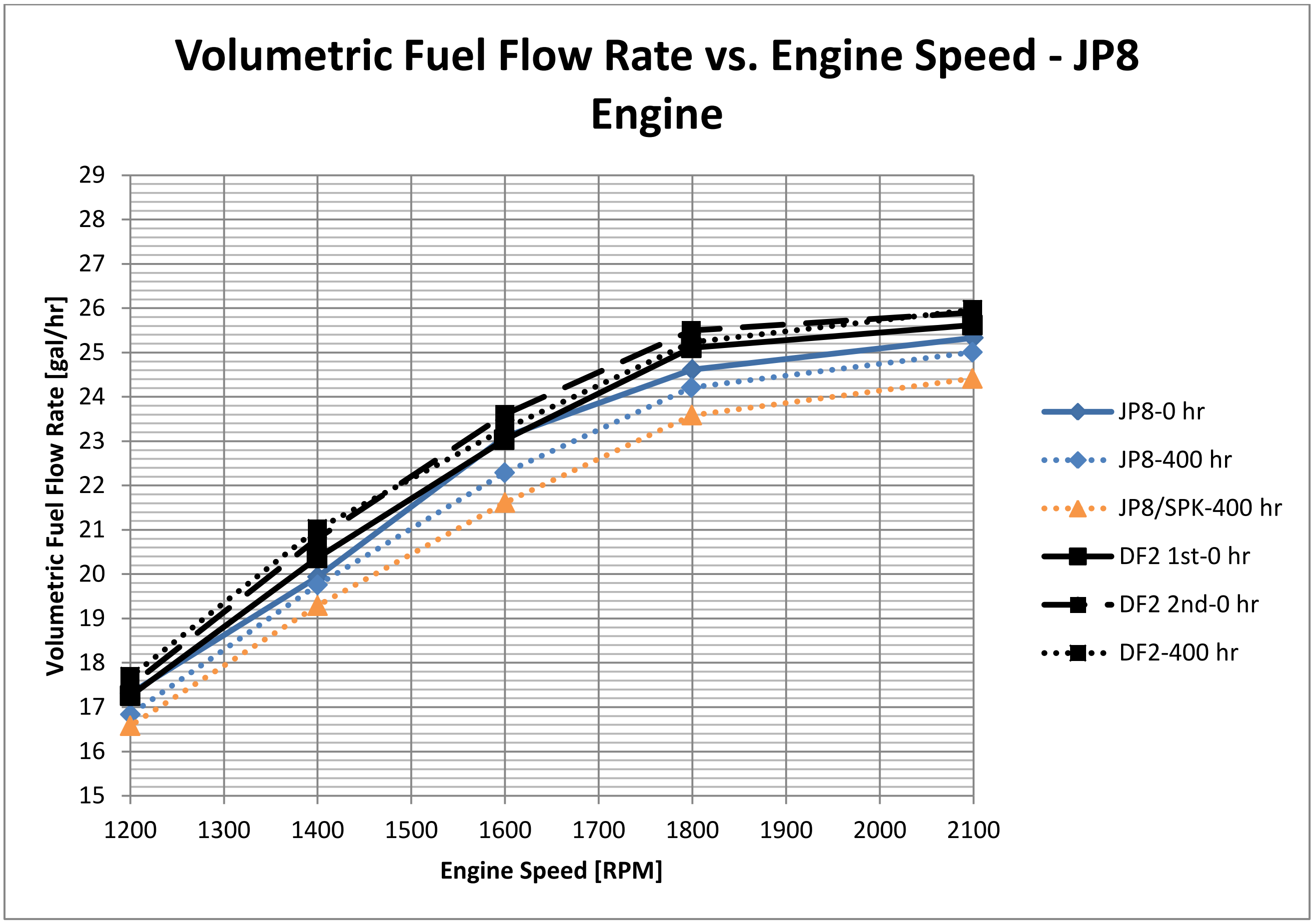

Figure 8. Graph comparing initial and final performance runs on JP-8 engine, depicting fuel flow rate vs. engine speed

JP-8/FT SPK blend fuel did not have a significant effect on the fuel system when compared to JP-8 fuel. Although a significant power drop was observed between the initial and final full load performance runs for the synthetic blend fuel (3.8% at rated power and 5.5% at rated torque), the cause was determined most likely to be from the damaged turbocharger. There was no loss of fuel flow rate between the initial performance runs and final performance runs on either engine. No additional wear was measured on fuel system components for utilizing the blend fuel compared to neat JP-8, and damage to the turbocharger may have been the greatest contributor to power degradation. Testing sample size was minimal, using only one baseline fuel engine and one synthetic fuel blend engine, and thus a definitive conclusion cannot be made without further testing.

3.0 Procedure and Setup

The durability and performance runs were conducted in a test cell at normal ambient conditions. The test cell does not have cooling capability so the ambient air temperature did vary over the duration of the test, although there was an acceptable variance between performance runs (see Table 1).

Table 1. Average cell temperatures during performance runs for both 8V92TA engines

Average Cell Temperatures During Performance Runs					
Engine	Performance Run (@ hours of NATO test)	Fuel	Performance Run Date	Average Ambient Cell Temperature (^oF)	Standard Deviation of Cell Temperature (^oF)
JP8/FT SPK Blend NATO	0	DF-2	26 APR 10	79.2	0.7
		JP8	27 APR 10	74.1	0.7
		JP8/FT SPK	28 APR 10	74.7	1.3
	100	JP8	17 MAY 10	77.9	0.8
		JP8/FT SPK	17 MAY 10	77.3	0.4
	200	JP8	08 JUN 10	75.8	1.8
		JP8/FT SPK	08 JUN 10	75.3	0.6
	300	JP8	26 JUN 10	77.5	0.5
		JP8/FT SPK	26 JUN 10	82.2	1.1
	400	JP8/FT SPK	20 JUL 10	77.3	0.7
		JP8	20 JUL 10	84.4	0.4
		DF-2	23 JUL 10	85.2	2.1
JP8 NATO	0	DF-2	31 AUG 10	87.3	0.8
		DF-2	01 SEP 10	89.0	1.3
		JP8	02 SEP 10	87.5	1.0
	100	DF-2	23 SEP 10	75.8	1.5
		JP8	23 SEP 10	85.7	1.3
	200	DF-2	13 OCT 10	61.4	1.4
		JP8	13 OCT 10	71.9	0.5
	300	DF-2	17 NOV 10	75.6	1.2
		JP8	17 NOV 10	80.8	0.9
	400	JP8	08 DEC 10	74.9	1.1
		DF-2	09 DEC 10	71.7	1.9
		JP8/SPK	10 DEC 10	74.0	1.2

3.1 Test Cell/Engine Setup

1. Prepare the engine for performance and endurance testing.
2. Install and calibrate all instrumentation (see Table 14, Appendix V).
3. Conduct engine and instrumentation inspection before test (check-out).
4. Bore scope engine and record images for visual inspection reference.
5. Conduct full load NATO Performance Test (refer to Table 10, Appendix III):
    a. With DF-2, JP-8 and JP-8/synthetic blend prior to start of standard NATO Endurance Test (Table 8, Appendix III).
    b. With JP-8 and JP-8/synthetic blend after completing every 100 hr endurance period

c. With DF-2, JP-8 and JP-8/synthetic blend after completing 400 hrs of standard NATO Endurance Test.

6. Record all data at the end of every 10 hour sub cycle. Provide daily test reports regarding incidents and data measurements for engineering analysis unless otherwise indicate.
7. Conduct all testing with the standard MIL Spec 15W-40 engine oil.
8. Change engine oil and filter after every 100 hours of engine test operation.
9. Conduct used engine oil sampling after every 100 hrs of engine test operation. Oil shall be purged from the engine only when fully warmed and well mixed to ensure a homogeneous representative sample.
10. Bore scope engine after every 100 hours during standard NATO endurance test and document images.
11. Check condition of injectors every 100 hours of standard NATO endurance test and clean if necessary.
12. Perform property characterization tests on the fuels indicated in the objectives section at 0 hr, 200 hr, and 400 hr
    a. Samples will be taken from the engines fuel delivery line after the fuel filter.
    b. Fuels will be characterized according to MIL DTL-83133F JP-8 and JP-8/SPK blend.
    c. In addition, viscosity at 40^{o}C and 100^{o}C will be measured for JP-8 and the blend. The derived Cetane number will also be measured for the blend.
13. Conduct all testing using an engine coolant of a 50/50 blend of ethylene glycol and water.
14. Maintain the following parameters while conducting all performance and endurance testing:

Table 2. Controlled test parameters

	NATO
Coolant Outlet Temp	205 ± 5 ºF
Induction Air Depression	-10 ± 2 in_$H_2$0
Exhaust Backpressure	16 ± 2 in_$H_2$0
Fuel Supply Temp	86 ± 5 ºF
Induction Air Supply Temp	77 ± 5 ºF

Note: Induction air depression and exhaust back pressure are to be set at rated condition and allowed to vary at other operating points

12. Additional information will be provided by the test engineer(s) as required. See Appendix B for additional information related to test procedures and protocol.
13. Coordinate an engine tear down with OEM (Detroit Diesel) in order to inspect the engine for wear and other associated problems after each NATO test.
14. Send out fuel injection pumps and injectors to Detroit Diesel for inspection and measurement after each NATO test.

3.1.1 Test Equipment

Two 8V92TA MTU/Detroit Diesel engines were used during this test, one of which utilized a 50/50 blend of JP-8 and FT SPK fuel and the second utilized JP-8 fuel. These engines were both rebuilt from MTU/DD central and specifications were checked at the manufacturing location after the rebuild to ensure that they complied with tolerances. All instrumentation was calibrated according to specifications.

Fuel

A break-in cycle was run on each engine using DF-2 fuel. The first engine test utilized the JP-8/FT SPK 50/50 blend fuel during the 400 hour NATO durability cycle, and the performance tests run on the engine at the beginning of the test, as well as after every 100 hour cycle, utilized both JP-8 and JP-8/FT SPK 50/50 blend fuel. DF-2 was used only at the initial (0 hour) and final (400 hour) performance runs in order to characterize the engine with the fuel that the manufacturer calibrated for. The second engine utilized JP-8 fuel for the 400 hour NATO durability test. DF-2 and JP-8 were run at the initial performance run and at the end of every 100 interval after that. The JP-8/FT SPK 50/50 blend fuel was used only at the final performance run since JP-8/FT SPK was not available at the test cell during the first four performance runs (0 hour, 100 hour, 200 hour, 300 hour). The fuel was tested for certain properties, which are listed in Table 6 and 7, Appendix II. There were no significant deviations between fuels of a given type.

Test Conditions

The test occurred in a cell that had limited temperature and humidity control. The temperature often varied within the same day, as would the humidity and barometer. The temperature conditions during the performance runs, however, varied by acceptable amounts, which are tabulated in Table 1.

Test Procedure

The goal of the test was to determine the performance and durability differences between JP-8 and JP-8/FT SPK 50/50 blend fuel. Two engines were run through a standard 400 hour NATO durability cycle: one on JP-8 fuel and the other utilizing JP-8/FT SPK 50/50 blended fuel. The engines were initially broken-in with DF-2 fuel. Performance runs were performed before the beginning of each durability test, as well as after each 100 hour cycle. The engines were disassembled to visually inspect for any wear that occurred, and the difference in wear of the two engines was compared against each other.

Performance Run

The full-load performance runs consisted of setting the engine to a given speed at full load and allowing the data to stabilize. The channeled parameters were then recorded. Each performance run consisted of two iterations of each engine speed to increase the accuracy of the data, beginning at rated speed and decreasing the engine to the next test condition. Performance runs were conducted before the durability test and after each 100 hour cycle. The fuel filters were changed when fuels were switched to prevent contamination. See Appendix III for a list of the performance runs.

4.0 Results and Discussion

The bore scope videos provided visual evidence that the fuel injectors had deposit build-up on their tips, but since the power did not rapidly decrease it was decided to complete testing with the synthetic blend fuel. Analysis was performed on the build-up material at disassembly on the cylinder table heads and it was found to contain oil package additives and evidence of fuel (see Appendix VIII, Table 22).

4.1 Engine Disassembly

Both 8V92TA MTU/Detroit Diesel engines were disassembled and visually inspected for abnormal amounts of wear.

4.1.1 Fischer-Tropsch derived Synthetic Paraffinic Kerosene and JP-8 Blend Engine Disassembly

The disassembly of the JP-8/FT SPK 50/50 blended engine revealed damage to the turbine side of the turbocharger. It was determined to be caused by a broken thermocouple probe located in one of the exhaust ports before the turbocharger, which failed after 140 hours of the NATO test. The turbocharger was not removed at this cycle because the data was not indicative of any heavy damage. After analyzing the data, the damaged turbocharger and resultant decrease in turbo boost was determined to be the primary cause of power degradation in the FT SPK/JP-8 (v) blended fuel engine.

The pistons and cylinder heads did not show any excessive wear. There was, however, excess build-up of what was determined to be a combination of oil and fuel (Appendix VIII, Table 22).

4.1.2 JP-8 Engine Disassembly

No excess wear was observed during the JP-8 engine disassembly. The piston crowns and cylinder heads did have excess debris build-up, which was expected and seen during the bore scope process (Figure 6). This can possibly be attributed to the lack of detergents and dispersants in JP-8 fuel as compared to DF-2 fuel. A sample was taken for analysis (Appendix VIII, Table 22) and the results suggest a combination of oil and fuel, similar to the JP-8/FT SPK engine.

4.2 Oil Consumption

Oil samples were taken and analyzed at every performance run. The JP-8/SPK engine burned 10.5 gallons of oil throughout the 400 hour NATO test while the JP-8 burned through 8.75 gallons. This difference in oil consumptions has a < 0.1% effect on engine energy addition throughout the durability test and does not have a significant effect on engine performance. Both the baseline fuel engine and synthetic fuel engine were rebuilds, and the difference in oil consumption is most likely a result of the rebuild tolerance differences. See Appendix I for a breakdown of oil consumption.

5.0 Engine Photos

5.0.1 Fischer-Tropsch derived Synthetic Paraffinic Kerosene and JP-8 Blend Engine Pictures

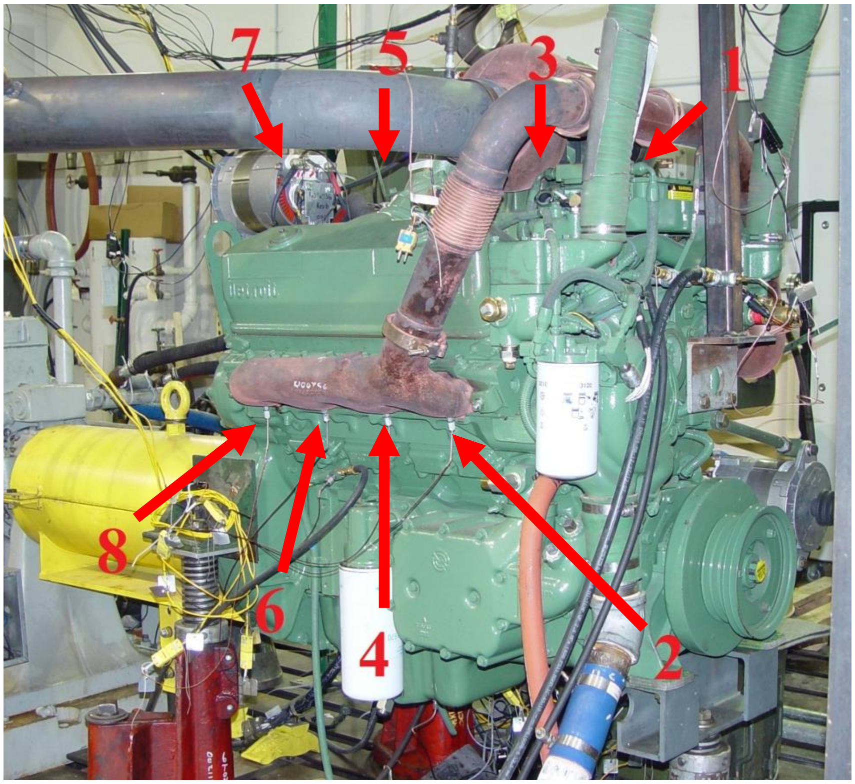

Figure 9. Labeled exhaust ports on 8V92TA engine

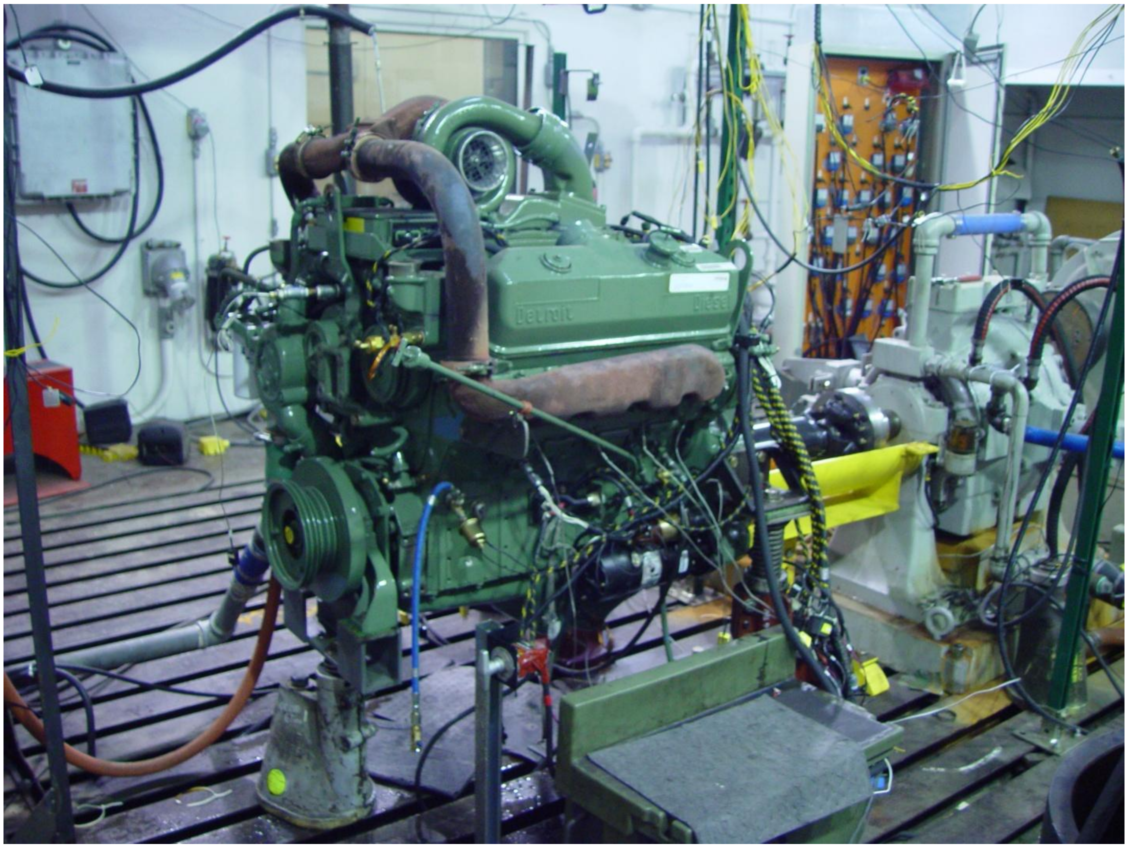

Figure 10. Left side of engine JP-8/SPK blend fuel engine during removal from cell

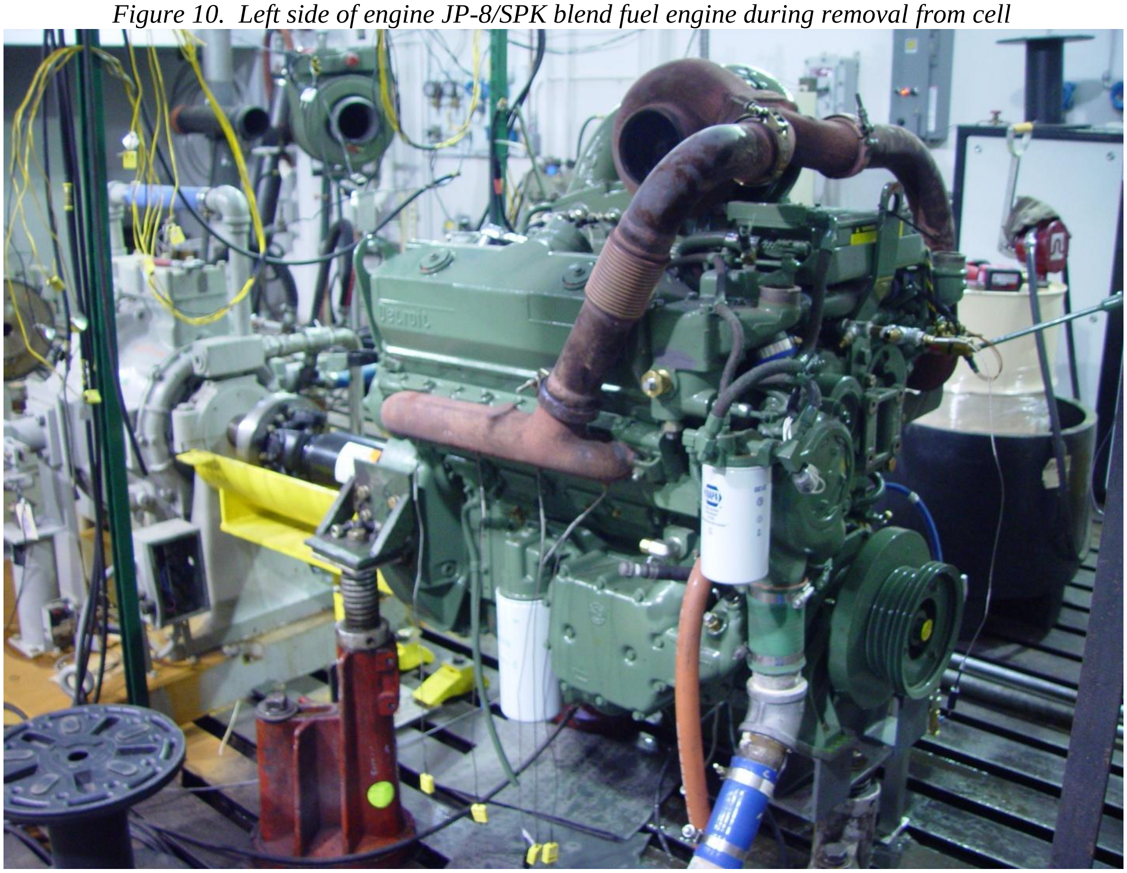

Figure 11. Right side of JP-8/SPK blend engine during removal from cell

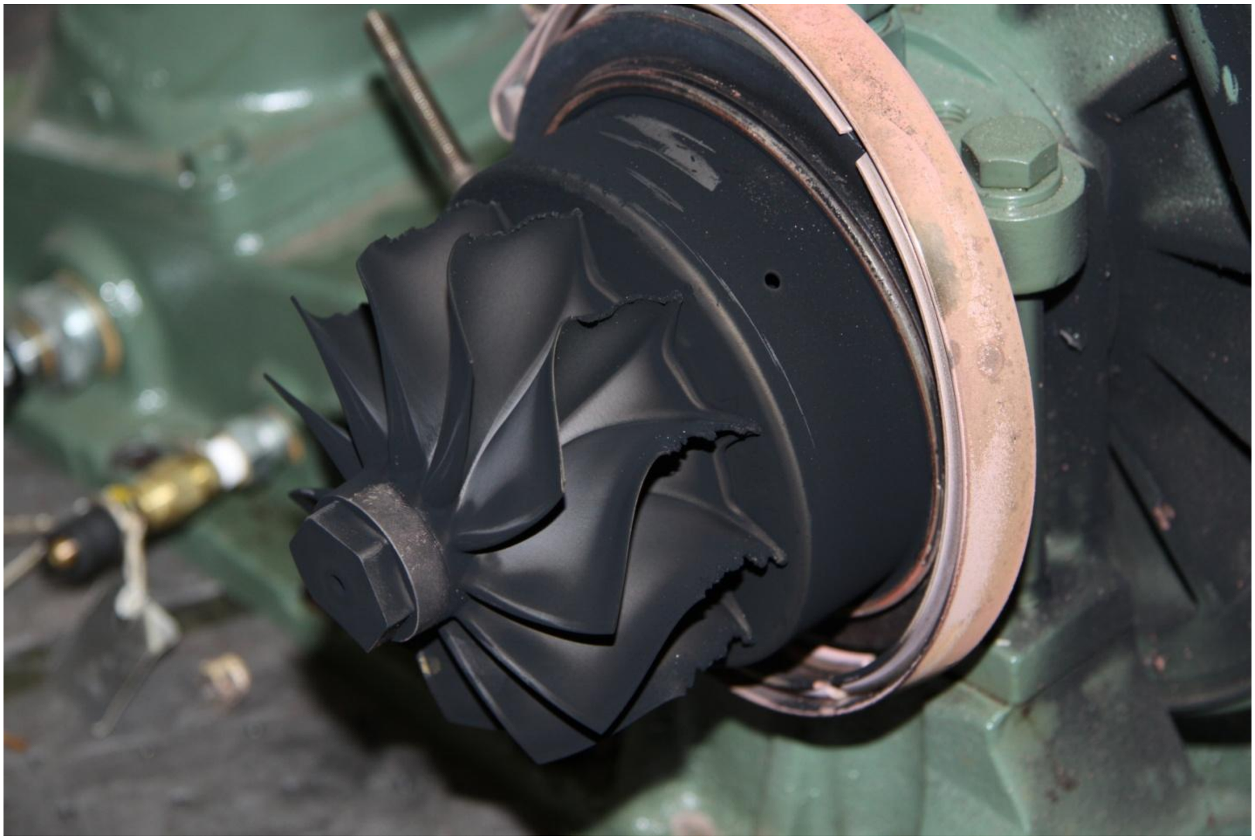

Figure 12. JP-8/FT engine damaged turbine blades on turbocharger

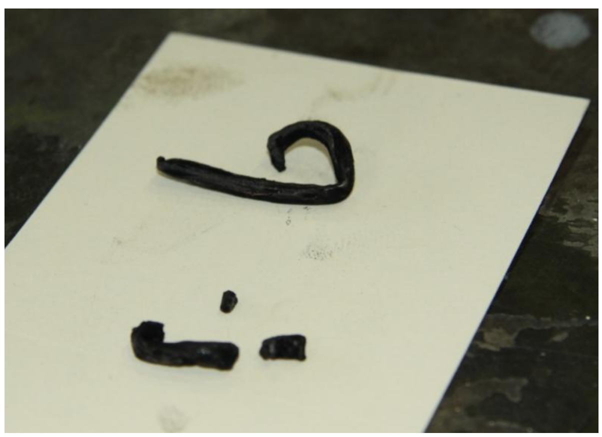

Figure 13. Recovered thermocouple probe from turbocharger housing on JP-8/FT engine

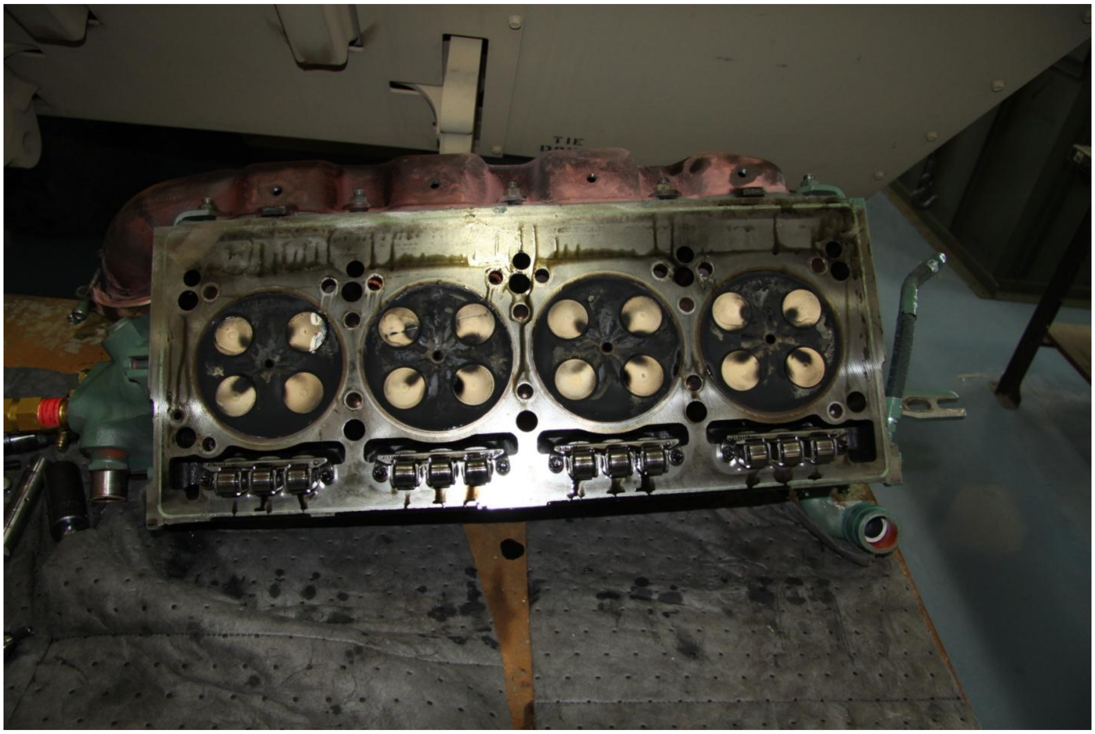

Figure 14. JP-8/FT engine cylinder heads 1,3,5,7 with debris build-up

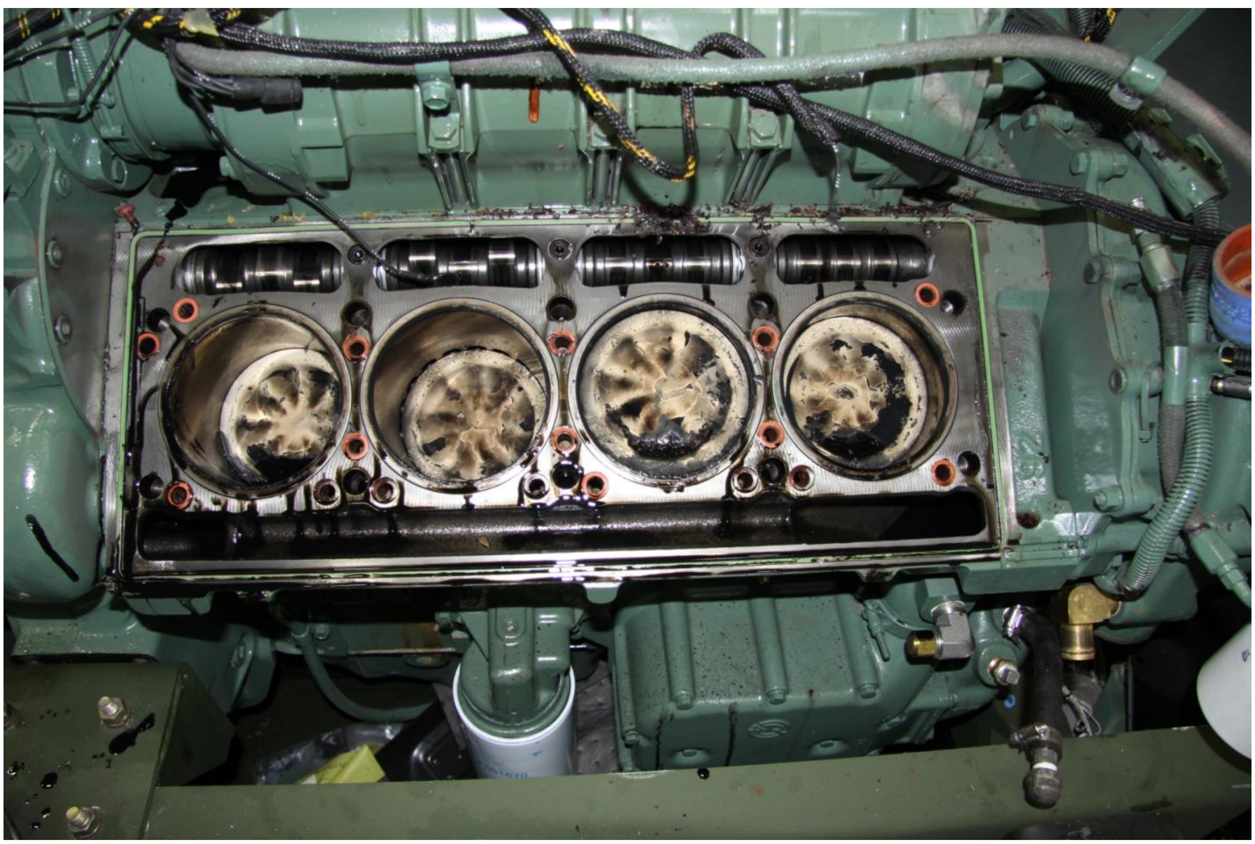

Figure 15. JP-8/FT engine piston heads with spray patterns and debris build-up for cylinders 2,4,6,8

5.0.2 JP-8 Engine Pictures

Figure 16. JP-8 cylinder heads with excess fuel and oil build-up for cylinders 1,3,5,7

Figure 17. JP-8 piston cylinders with excess build-up on piston heads for cylinders 2,4,6,8

Appendix Table of Contents

Appendix

I. Analysis of New and Used Oil

Table 3. Oil analysis of JP-8/SPK blend engine

8V92TA Test, Engine #2

Sample Number		FL-13629-10	FL-13630-10	FL-13631-10
		5/13/2010	6/3/2010	8/5/2010
Work Order		WO#00783		
Hours of Engine Operation	MC-3891	100 hours	200 hours	400 hours
ASTM D 5185 - Wear Metals by ICP (ppm)				
Ag		<1	<1	<1
Al		2.6	2.7	2.4
B	0	19.5	9.5	4.9
Ba	0	2.2	1.9	<1
Ca	2080 - 2770	3206.0	3330	2583
Cd		<1	<1	<1
Cr		2.6	3.3	2.7
Cu		33.1	11.2	4.7
Fe		46.2	48.5	44.8
K		5.0	1.8	<1
Mg	100 - < 300	75.7	28.7	293.7
Mn		1.8	1.1	<1
Mo		2.6	1.7	2.5
Na	0	32.1	19.9	13.7
Ni		<1	0.4	<1
P	1150 - 1530	1130	1144	1264
Pb		22.4	9.1	4.0
Si		31.5	19.6	13.7
Sn		29.5	15.2	10.3
Ti		<1	<1	<1
V		<1	<1	<1
Zn	1260 - 1690	1427	1415	1455
ASTM D 664 - Total Acid Number (mgKOH/g)		3.52	3.62	3.14
ASTM D 4739 - Total Base Number	10.2	7.23	7.53	8.10
ASTM D 445 - Kinematic Viscosity @ 40C (cSt)	118.1	99.63	99.51	105.70
ASTM D 445 - Kinematic Viscosity @ 100C (cSt)	15.7	13.43	13.54	13.90
ASTM D 2270 - Viscosity Index		134.0	136.0	132.5
ASTM D 6304 - Water Content (%)		0.028	0.022	0.024
Soot Content by Soot Meter		0.1	0.25	0.3

Table 4. Oil analysis of JP-8 fuel engine

8V92TA Test, Engine #3

Sample Number		FL-13689-10	FL-13748-10	FL-13749-10	FL-13780-10	FL-43862-11
Work Order		WO#00792	WO#00808		WO #00821	WO #00841
Hours of Engine Operation		0 hours				
Hours on Oil	MC-3891	0 hours	100 hr	200 hr	300 hr	400 hr
ASTM D 5185 - Wear Metals by ICP (ppm)						
Ag		<1	<1	<1	<1	<1
Al		2.7	2.4	1.3	1.4	<1
B	0	1.4	1.3	<1	2.1	2.7
Ba	0	192.2	20.2	2.8	<1	<1
Ca	2080 - 2770	2456.0	2309	2284	2830	2940
Cd		<1	1	<1	<1	<1
Cr		1.1	1.3	1.6	1.8	2.5
Cu		21.2	9.4	4.8	3.8	4.1
Fe		23.3	38.7	36.4	45.5	76.4
K		3.8	3.5	2.9	1.8	1.8
Mg	100 - < 300	223.3	249	252.3	158.9	23.9
Mn		1.1	<1	<1	<1	<1
Mo		2.2	2.1	2.1	1.4	<1
Na	0	26	29.9	17.2	14.7	9.0
Ni		<1	2.1	1.3	<1	<1
P	1150 - 1530	1338	1010	995	1209	1088
Pb		25.2	20.7	8.8	9.4	7.0
Si		25.3	32.9	18.8	14.6	16.5
Sn		40.9	29.5	15.3	8.1	6.4
Ti		<1	<1	<1	<1	<1
V		<1	<1	<1	<1	<1
Zn	1260 - 1690	1450	1297	1345	1417	1254
ASTM D 664 - Total Acid Number (mgKOH/g)		2.90	2.61	2.62	3.39	2.99
ASTM D 4739 - Total Base Number	10.2	8.66	7.23	7.69	7.72	7.43
ASTM D 445 - Kinematic Viscosity @ 40C (cSt)	103.1 - 133.1	103.9	100.9	100.30	99.37	96.64
ASTM D 445 - Kinematic Viscosity @ 100C (cSt)	15.2 - 16.2	13.97	13.47	13.48	13.33	13.17
ASTM D 2270 - Viscosity Index		136.0	133.0	134.0	133.0	135.0
ASTM D 6304 - Water Content (%)		0.012	0.011	0.005	0.007	0.005
Soot Content by Soot Meter		0.0	0.0	0.0		

The results of oil testing did not suggest a significant wear on the engine components. The high levels of barium measured in the JP-8 fuel engine at 0 hours are most likely from the storage of the engine, as barium is a metal found in some oil additives and greases.

Table 5. Oil consumption during NATO testing

Oil Consumption		
		JP-8/SPK Engine
Cycle	Date	[Qrts]
1	4/29/2010	
2	4/30	3
3	5/3	1
4	5/4	
5	5/5	2
6	5/6	
7	5/7	2
8	5/10	2
9	5/11	
10	5/12	2
11	5/18	
12	5/19	2
13	5/20	
14	5/21	2
15	5/24	
16	5/25	2
17	5/26	
18	5/27	2
19	6/1	
20	6/2	
21	6/9	2
22	6/10	
23	6/11	2
24	6/14	
25	6/15	
26	6/16	2
27	6/20	
28	6/21	
29	6/22	2
30	6/23	
31	6/27	
32	6/29	2
33	6/30	2
34	7/1	
35	7/8	2
36	7/9	2
37	7/13	2
38	7/14	2
39	7/15	
40	7/18	2
	Total:	42

Oil Consumption		
		JP-8 Engine
Cycle	Date	[Qrts]
1	9/8/2010	
2	9/9	
3	9/10	3
4	9/13	2
5	9/14	
6	9/15	3
7	9/16	
8	9/17	3
9	9/20	3
10	9/22	
11	9/27	
12	9/28	
13	9/29	2
14	9/30	
15	10/1	3
16	10/4	
17	10/5	2
18	10/6	2
19	10/7	
20	10/8	
21	10/14	
22	10/15	
23	10/18	2
24	10/19	
25	10/20	2
26	10/21	
27	10/25	2
28	10/26	
29	10/28	2
30	11/1	
31	11/18	
32	11/19	
33	11/22	2
34	11/23	
35	11/29	
36	11/30	
37	12/2	2
38	12/3	
39	12/4	
40	12/5	
	Total:	35

The JP-8/FT SPK blended fuel engine used 7 more quarts of oil (12.89 lbs) than the JP-8 neat fuel engine did over the course of the 400 hour NATO test. The AVL 415S smoke detector did not detect any significant amounts of smoke during either engines' NATO test.

Since some oil enters the combustion chamber in a 2-stroke engine, 7 quarts is a small difference over a 400 hour cycle. Tolerance differences between the two engines may account for the oil consumption difference.

$$\rho_{oil} = 1.8408\ lb_m/qrt$$
$$7\ qrts * 1.8408\ lb_m = 12.8856\ lb_m$$

The heat of combustion of oil is more than that of the fuel, but assuming fuel as a higher end limit for heat of combustion:

$$h_{oil} \approx 19{,}800 \frac{Btu}{lb_m}\ [6]$$

The mass flow of the additional oil added to the JP-8/FT SPK blend engine can be calculated as:

$$\dot{m}_{oil} = \frac{m_{oil}}{time} = \frac{12.8856\ lb_m}{400hr * 60\ \frac{min}{hr}} = 5.369x10^{-4}\ \frac{lb_m}{min}$$

Total energy addition due to additional oil:

$$\dot{m}_{oil} * h_{oil} = 5.369x10^{-4}\ \frac{lb_m}{min} * 19800\ \frac{Btu}{lb_m} = 10.6306\ \frac{Btu}{min}$$

Energy balance calculations show about a 35,500 Btu/min energy input to the engine from air and fuel averaged over a 10 hour cycle (see Appendix VI for calculation). A low estimate was used, which will result in a higher perceived oil effect. If oil is also added to this initial energy, assuming 100% of the additional oil contributes to the total energy of the engine, an approximate difference can be calculated as below:

$$\frac{10.6306\ \frac{Btu}{min}}{35{,}500 \frac{Btu}{min}} = .0003 \approx 0.03\%$$

This is an upper limit and therefore will have a < 0.03% effect on the power and temperature output of the engine, a negligible effect.

II. Fuel Analysis

Table 6. JP-8/FT SPK engine fuel properties

JP8/FT SPK Engine Fuel Properties

Property	ASTM D	MIL-DTL-63133G, Table 1		FL-13513-10	FL-13514-10	FL-13515-10	FL-13568-10	FL-13567-10	FL-13587-40	FL-13604-10
			Fuel:	JP8	JP8/FT SPK Blend	DF2	JP8/FT SPK Blend	JP8	JP8	JP8/SPK FT Blend
			Relevant FPR:	0, 100	0, 100	0	200	100, 200, 300	400	400
		Min	Max	09 APR 10	29 APR 10	29 APR 10	18 JUN 10	18 JUN 10	14 JUL 10	29 JUL 10
Saybolt Color	156*	report		+20	+16	+5.6	+19	+22	+25	+19
TAN, mg KOH.g	3242		0.015	0.008	0.0042	0.0093	0.0050	0.0043	0.0045	0.0069
Aromatics, vol %			25.0	14.5	10.6	28.4	9.1	14.7	10.70	9.3
Olefins, vol %	1319				1.3	2.2	1.3			0.9
Saturates, vol %					88.1	69.4	89.6			89.8
Sulfur, total, mass percent	2622		0.30	0.094	0.006	0.006	0.0008	0.0905	0.0348	0.0007
Distillation, °C										
IBP		report		159.8	156.8	161.1	155.5	175.7	157.9	157.7
10%			205	185.0	170.1	216.6	168.1	193.2	183.8	168.0
20%		report		192.0	174.2	232.1	171.2	165.4	191.6	171.1
50%		report		207.3	189.0	263.6	184.1	209.2	208.8	183.7
90%	86* / 7345	report		238.1	223.9	312.8	217.1	237.5	240.1	217.4
FBP			300	253.3	247.7	337.8	236.1	250.7	256.4	236.1
T50-T10		15			18.9		16			15.7
T90-T10		40			53.8		49.0			49.4
Residue, vol %			1.5	1.3	1.3	1.8	1.3	1.3	1.4	1.4
Loss, vol %			1.5	0.8	0.7	0.1	0.7	0.8	0.6	0.6
Flash Point, °C	93*	38		45.3	47.3	58.3	47.9	58.4	49.4	47.9
Density, kg/L @ 15°C	1298	0.775	0.840	0.8036	0.7819		0.7746	0.8059	0.8027	0.7746
	4052*			0.8042	0.7873	0.8472	0.775	0.8061	0.8036	0.7744
API gravity @ 60°F	1298	37.0	51.0	44.5	49.4		51.1	44.0	44.7	51.1
	4052*			44.3	49.2	35.37	50.9	43.9	44.4	51.0
Cloud Point, °C	7346					-20.0				
Pour Point, °C						-39.0				
Cold Filter Plugging Point (CFPP), °C	6371									
Freezing Point, °C	5972*		-47	-48.0	-64.5		-65.5	-39.6	-50.7	-67.0
	7153			-49.0	-62.7		-66.9	-48.7	-52.5	-65.7
Viscosity, mm^2/s										
40	445	not required		1.3825	1.159		1.101	1.441	1.406	1.092
-20			8.000	4.798	3.0732		3.219	5.096	4.9705	3.204
Viscosity, mm^2/s										
40	7042	not required								
-20			8.000							
Net Heat of Combustion, MJ/kg	3338	42.8		43.3	43.6	42.9	43.7	43.3	43.4	43.7
Hydrogen Content, mass %	3343	13.4		13.9	14.4	13.2	14.5	13.9	14.1	14.5
Calculated Cetane Index	976*	report		46.0	47.5	46.9	48.4	45.8	47.0	48.2
	4737			47.5	50.4	46.6	52.0	47.5	48.5	51.9
IQT - Derived Cetane Number	6890	not required		19.64	47.15		49.00	19.79	47.95	47.99
	7668									
Copper Strip Corrosion	130		No. 1	1a	1a	1a	1a	1a	1a	1a
Thermal Stability (JFTOT)										
change in pressure drop, mmHg	3241		25	0.0	0.00		0.01	0.00	0.00	0.00
heater tube deposit, visual rating			< 3	<1	<1		<1	1	<1	<1
Existent Gum, mg/100mL	381		7.0	0.5	1.9		1.1	1.1	0.8	0.8
Ash, mass %	482									
Particulate Matter, mg/L (0.8micron)	6217		1.0	0.4	0.4	1.4	0.6	0.4	0.3	0.1
MCRT, mass %	4530					0.025				
Water Separation Index	3948	70^		47	72		83	52	48	78
Fuel System Icing Inhibitor (FSII), vol. %	5006	0.10	0.15	0.13	0.13		0.12	0.105	0.10	0.11
Fuel Electrical Conductivity, ps/m	2624	150	450, 600	281	246		138	203	299	205
HFRR [average wear scar, micron]	6079									
BOCLE, avg, wear scar (mm)	5001	not required					0.56	0.57	0.57	0.54

*=Referee Test Method

^=Minimum Microseparometer reading dependent on types of additives in fuel

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

Table 7. JP-8 engine fuel properties

JP8 Engine Fuel Properties								
Property	ASTM D	MIL-DTL-63133G, Table 1		FL-13759-10	FL-13768-10	FL-13789-10	FL-13804-10	FL-13803-10
			Fuel:	JP8	JP8	JP8	JP8/FT SPK Blend	DF2
			Relevant FPR:	0	300	400	400	400
		Min	Max	18 AUG 10	10 NOV 10	29 NOV 10	15 DEC 10	15 DEC 10
Saybolt Color	156*	report		+16	-3	+22	+17	+5.7
TAN, mg KOH.g	3242		0.015	0.0056	0.0041	0.0054	0.006	0.013
Aromatics, vol %	1319		25.0	10.4	9.9	15.7	9.6	28.7
Olefins, vol %				1.1	1.4			
Saturates, vol %				88.5	88.7			
Sulfur, total, mass percent	2622		0.30	0.04	0.02	0.08	0.0006	0.0007
Distillation, °C								
IBP		report		165.3	165.7	177.3	159.5	176.2
10%			205	186.2	186.1	194.0	168.2	214.3
20%		report		193.4	196.3	199.1	171.8	227.4
50%		report		209.0	215.3	242.5	184.0	257.7
90%	86* / 7345	report		236.9	244.6	239.4	217.5	305.1
FBP			300	251.4	269.0	252.5	247.2	333.2
T50-T10		15						
T90-T10		40						
Residue, vol %			1.5	1.4	1.4	1.3	1.3	1.5
Loss, vol %			1.5	0.7	0.5	0.7	0.6	0.0
Flash Point, °C	93*	38		53.5	55.0	58.0	49.0	63.0
Density, kg/L @ 15°C	1298	0.775	0.840	0.8013		0.8087	0.775	0.8443
	4052*			0.8005	0.8040	0.8088	0.775	0.8433
API gravity @ 60°F	1298	37.0	51.0	45.0		43.4	51.1	36.0
	4052*			45.11	44.33	43.29	51.0	36.2
Cloud Point, °C	7346							-24.0
Pour Point, °C								-27.0
Cold Filter Plugging Point (CFPP), °C	6371							-25.0
Freezing Point, °C	5972*		-47					
	7153			-53.1	-51.4	-47.4	-54.5	
Viscosity, mm²/s	445							
40		not required		1.356		5.417	3.498	2.419
-20			8.000	4.975		1.48	1.098	1.033
Viscosity, mm²/s	7042							
40		not required		1.4522	1.4939	5.4379	3.218	2.431
-20			8.000	5.0192	5.4961	1.4834	1.114	1.049
Net Heat of Combustion, MJ/kg	3338	42.8		43.4	43.4	43.3	43.6	42.9
Hydrogen Content, mass %	3343	13.4		14.1	14.1	13.8	14.5	13.2
Calculated Cetane Index	976*	report		47.6	48.9	46.0	48.4	46.9
	4737			49.0	50.0	47.2	52.0	46.8
IQT - Derived Cetane Number	6890	not required		47.22	46.85	49.73	48.2	44.0
	7668						50.6	47.1
Copper Strip Corrosion	130		No. 1	1a	1b	1a	1a	1a
Thermal Stability (JFTOT)	3241							
change in pressure drop, mmHg			25	2		5.41	0	
heater tube deposit, visual rating			< 3	<1		<4	<1	
Existent Gum, mg/100mL	381		7.0	1.5	4.2	1.4	1.4	
Ash, mass %	482		0.01					0.0002
Particulate Matter, mg/L (0.8micron)	6217		1.0	0.7		0.6	0.0	1.2
MCRT, mass %	4530							0.009
Water Separation Index	3948	70^		41	68	0	76	
Fuel System Icing Inhibitor (FSII), vol. %	5006	0.10	0.15	0.11		0.11	0.11	
Fuel Electrical Conductivity, ps/m	2624	150	450, 600	453	157	324	166	579
HFRR [average wear scar, micron]	6079		520					395
BOCLE, avg, wear scar (mm)	5001	not required		0.56	0.57	0.56	0.57	

*=Referee Test Method

^=Minimum Microseparometer reading dependent on types of additives in fuel

III. Engine Performance and Endurance Test Procedures

Table 8. Engine test timeline

ENGINE #1

DF-2 Full Load NATO
Change Fuel Filter
JP-8 Full Load NATO
Change Fuel Filter
SPK/JP-8 Full Load NATO
SPK/JP-8 Part Load NATO
Change Oil/Oil Filter
Standard Endurance NATO Test w/ SPK/JP-8
SPK/JP-8 Full Load NATO
Change Fuel Filter
JP-8 Full Load NATO
Change Fuel Filter
DF-2 Full Load NATO

ENGINE #2

DF-2 Full Load NATO
Change Fuel Filter
SPK/JP-8 Full Load NATO
Change Fuel Filter
JP-8 Full Load NATO
JP-8 Part Load NATO
Change Oil/Oil Filter
Standard Endurance NATO Test w/ JP-8
JP-8 Full Load NATO
Change Fuel Filter
SPK/JP-8 Full Load NATO
Change Fuel Filter
DF-2 Full Load NATO

Engine Performance Test Procedure

The performance test maximum load curve will be plotted from measurements taken at speeds shown in Table 9. For each setting, the engine should be run for a sufficient amount of time to allow the operating parameters to stabilize and achieve steady-state.

Table 9. Performance test points

Speed (RPM)	% Throttle
1200	100
1400	100
1600	100
1800	100
2100	100

Part load data is to be recorded at the same pre-selected speeds as was used for the full load test. The part loads for each speed point are to be calculated for 85%, 70%, and 50% of the full load at the given speed. During this test, the smoke emissions as measured on the BOSCH Scale (or equivalent) shall not exceed 4.5.

Engine Endurance Test Procedure

The engine shall be subjected to a 400 hour endurance test as specified in AEP-5 at standard NATO conditions as defined in Table 2, test parameter conditions. Data shall be recorded during the last five minutes of each sub-cycle excluding sub-cycle 5. If the engine and/or its subsystems exceeds established limit conditions and the sub-cycle must be aborted, the sub-cycle may be restarted from the beginning, pending an Engineer's decision. The engine may be turned off upon completion of any sub-cycle and may later be restarted into the next sub-cycle without penalty.

Table 10. Endurance test ten hour cycle

Definition of 10 Hour Cycle				
Sub-Cycle	% Rated Speed	RPM	% Load	Duration in hrs
1	Idle (1)(7)	-	0	0.5
2	100	2100	100 (5)	2
3	Governed speed (2)	2150	0	0.5
4	75	1575	100 (5)	1
5	Idle (1)_(3)_100		0(4min)__100(6min)	2
6	60	1260	100	0.5
7	Idle (1)(7)	-	0	0.5
8	Governed speed (4)	2150	70 (6)	0.5
9	Max Torque Speed	1400	100 (5)	2
10	60	1260	50 (6)	0.5
Total				10

1. Deviation from regulated coolant and fuel temperature is permitted in this sub-cycle
2. The engine speed shall be obtained with the engine at full throttle and with minimum load
3. The control movement from IDLE to 100% rated speed/load shall occur within 3 seconds
4. The engine speed shall be the steady speed of the engine at full throttle and 70% of the rated load
5. One-hundred percent load shall be governed by full throttle
6. Part loads shall be determined based on the initial performance test
7. A small load may be applied to reduce vibration damage to the test prop-shaft

IV. Fuel Delivery Dates

Table 11. Fuel delivery and sample dates

Fuel Delivery and Sample Table				
Notes	**Date**	**Description**	**Fuel Sample**	**Use for FLPR**
		JP-8/FT SPK Engine		
	2010-04-09	JP-8 Fuel Sample	FL-13513-10	0, 100
Use for 0 hr Sample	2010-04-09	JP-8/SPK Fuel Sample	FL-13514-10	0, 100
	2010-04-09	DF-2 Fuel Sample	FL-13515-10	0
	2010-04-26	0 hr DF-2		
	2010-04-27	0 hr JP-8		
	2010-04-28	0 hr JP-8/SPK		
	2010-05-17	100 hr JP-8		
	2010-05-17	100 hr JP-8/SPK		
	2010-06-08	200 hr JP-8		
	2010-06-08	200 hr JP-8/SPK		
	2010-06-18	JP-8 Fuel Sample	FL-13567-10	100, 200, 300
	2010-06-19	JP-8/SPK Delivery		
	2010-06-26	300 hr JP-8		
	2010-06-26	300 hr JP-8/SPK		
2010-06-30	2010-07-07	JP-8/SPK Fuel Sample	FL-13575-10	300
	2010-07-14	JP-8/SPK Delivery		
	2010-07-14	JP-8 Fuel Sample	FL-13587-10	400
	2010-07-20	400 hr JP-8/SPK		
	2010-07-20	400 hr JP-8		
	2010-07-23	400 hr DF-2		
	2010-07-29	JP-8 Fuel Sample	FL-13603-10	
Use for 400 hr Sample	2010-07-29	JP-8/SPK Fuel Sample	FL-13604-10	400
		JP-8 Engine		
	2010-08-17	JP-8 Delivery		
Analyzed 2010-10-20	2010-08-18	JP-8 Fuel Sample	FL-13759-10	0
	2010-08-31	0 hr DF-2		
	2010-09-01	0 hr DF-2		
	2010-09-02	0 hr JP-8		
	2010-09-21	JP-8 Delivery		
	2010-09-23	100 hr DF-2		
	2010-09-23	100 hr JP-8		???
	2010-10-13	200 hr DF-2		
	2010-10-13	200 hr JP-8		???
	2010-10-18	JP-8 Delivery		
	2010-11-10	JP-8 Fuel Sample	FL-13768-10	300
	2010-11-17	300 hr DF-2		
	2010-11-17	300 hr JP-8		
	2010-11-23	JP-8 Delivery		
	2010-11-29	JP-8 Fuel Sample	FL-13789-10	400
	2010-12-08	400 hr JP-8		
	2010-12-09	400 hr DF-2		
	2010-12-10	400 hr JP-8/SPK		
From Barrel	2010-12-15	JP-8/SPK Fuel Sample	FL-13804-10	400
	2010-12-15	DF-2 Sample	FL-13803-10	400

Table 11 lists the dates of fuel delivery and fuel samples. The rightmost column indicates which fuel sample was used for the corresponding performance run or runs for the energy balance equations. If no fuel sample corresponds to a performance run, an estimate of the fuel properties was used.

V. Measurement Parameters

The following parameters are to be measured or derived and recorded using standard laboratory instrumentation procedures.

a) Engine Crankshaft Speed (RPM)
b) Engine Output Torque (lb-ft)
c) Engine Output Power (bHp)
d) Ambient Air Temperature (ºF)
e) Atmospheric Pressure (psi)
f) Atmospheric Relative Humidity (%)
g) Induction Air Temperature (ºF)
h) Inlet Air Depression (in H_20)
i) Exhaust Backpressure (in H_20)
j) Exhaust Temperature Before Turbine (ºF)
k) Exhaust Temperature After Turbine (ºF)
l) Air Temperature After Compressor (ºF)
m) Oil Sump Temperature (ºF)
n) Oil Pressure (psi)
o) Fuel Supply Temperature (ºF)
p) Fuel Consumption (lb/hr)
q) Brake Specific Fuel Consumption (lb/Hp-hr)
r) Blow By Gas Flow (CFM)
s) Coolant Outlet Temp (ºF)
t) Coolant Inlet Temp (ºF)
u) Exhaust Smoke Bosch (FSN)
v) Mass Air Flow (lb/hr)
w) Heat Rejection (BTU/min)

Warning and shut down limits were not provided by Detroit Diesel. A typical performance sheet was supplied and used as the baseline for specifying warning values. The criticality of a warning condition will be assessed by the operator and provide a cause of action of either initiating a shut down procedure or informing through daily report and timely review

Table 12. Global Oil temperature limits

	Maximum Value	Minimum Value
Engine Speed	2250 RPM	600 RPM
Oil Gallery	70 psig	5 psig

Table 13. Oil temperature limits at rated speed (2100 RPM)

Oil Gallery	70 psig	49 psig

Table 14. Instrumentation list

CHANNEL NAME	DESCRIPTION	Data Log
SPEED		Y
TORQUE		Y
BHP		Y
THROTTLE POSIT		Y

CHANNEL NAME	DESCRIPTION	Data Log
pBARO		Y
HUMIDITY		Y
BSFC		Y
CELL AMBIENT (1)	YOKO ambient control temp	N
CELL AMBIENT (2)	YOKO ambient control temp	N
CELL AMBIENT (3)	YOKO ambient control temp	N
AIR AMBIENT		Y
AIR B4 COMP	Inlet to air compressor	Y
AIR INTAKE MANIF		Y
AIR TEST CELL DEPRES	0-1 PSI	Y
AIR TRANS RACK DELTA P	0-1 PSI	Y
AIR INLET RESTRICTION	0-1 PSI	Y
AIR FLOWMTR IN	0-10 in H2O	Y
AIR FLOWMTR OUT	0-25 PSI	Y
AIR AFTR COMP		
INLET AIR FLOW		Y
ENG COOLANT IN	Coolant entering the engine	Y
ENG COOLANT OUT	Coolant exiting the engine	Y
WTR TOWER IN	Building water into tower	Y
WTR TOWER OUT	Building water out of tower	Y
COOLANT TWR	Cap pressure (0-10 PSI)	Y
WTR TOWER MAGFLO	Building water flow into tower	Y
COOLANT TWR HT REJCT		Y
EXH PORT 1		Y
EXH PORT 2		Y
EXH PORT 3		Y
EXH PORT 4		Y
EXH PORT 5		Y
EXH PORT 6		Y
EXH PORT 7		Y
EXH PORT 8		Y
EXH B4 TURBO 1	Exhaust bank 1 into turbo	Y
EXH B4 TURBO 2	Exhaust bank 2 into turbo	Y
EXH STACK	Downstream of turbo	Y
OIL SUMP		Y
OIL GALLERY		Y
EXH B4 TURBO 1	0-60 PSI	Y
EXH B4 TURBO 2	0-60 PSI	Y
EXH BACK PRES	0-1 PSI	Y

CHANNEL NAME	DESCRIPTION	Data Log
CRANKCASE	0-3 PSI	Y
OIL GALLERY	0-60 PSI	Y
BLOW-BY		Y
AIR/FUEL RATIO	Lambda Meter	Y
SMOKE METER	AVL 415S	Y
FUEL BEAKER		Y
FUEL B4 HTR		Y
FUEL AFTR HTR		Y
FUEL SUPPLY		Y
FUEL RETURN		Y
BUILDING FUEL SUPLY	0-30 PSI	N
FUEL B4 FILTER	0-3 psi	Y
FUEL FLOW		Y
DYNO WTR IN		N
DYNO WTR OUT		N
FUEL HTR SUPPLY		N
FUEL HTR RETURN		N
STEAM HTR SUPPLY		N
STEAM HTR RETURN		N
TRANSDUCER RACK		N
BUILDING COOLING TWR	0-100 PSI	N
BUILDING DYNO WTR	0-60 PSI	N

VI. Energy Balance and Temperature Analysis

Table 15. JP-8/SPK engine temperature analysis

JP-8/SPK Engine Exhaust Temperature Delta between 400 hour FLPR and 0 hour FLPR					
RPM	Fuel	Exhaust Before Turbo 1	Exhaust Before Turbo 2	Exhaust Before Turbo 1	Exhaust Before Turbo 2
		Delta ^oF	Delta ^oF	Delta %	Delta %
2100	DF-2	21.44	65.93	2.24	6.54
	JP-8	24.66	66.43	2.69	6.95
	JP-8/SPK	27.21	48.78	3.06	5.20
1800	DF-2	21.25	43.85	2.07	4.33
	JP-8	25.03	53.95	2.58	5.62
	JP-8/SPK	33.33	50.48	3.59	5.39
1600	DF-2	22.15	51.80	2.24	5.47
	JP-8	39.53	54.48	4.21	5.99
	JP-8/SPK	29.03	55.50	3.16	6.29
1400	DF-2	29.50	62.53	3.10	7.17
	JP-8	44.63	75.75	4.92	9.10
	JP-8/SPK	31.55	63.58	3.54	7.72
1200	DF-2	39.85	68.40	4.34	8.50
	JP-8	50.38	77.25	5.71	9.93
	JP-8/SPK	40.70	71.33	4.67	9.29
			Average	3.47	6.90
			St. Dev	1.09	1.68

Table 16. JP-8 engine temperature analysis

JP-8 Engine Exhaust Temperature Delta between 400 hour FLPR and 0 hour FLPR					
RPM	Fuel	Exhaust Before Turbo 1	Exhaust Before Turbo 2	Exhaust Before Turbo 1	Exhaust Before Turbo 2
		Delta ^oF	Delta ^oF	Delta %	Delta %
2100	DF-2-1	40.67	27.13	4.40	2.78
	DF-2-2	18.76	25.49	1.97	2.61
	JP-8	19.52	22.41	2.13	2.37
1800	DF-2-1	34.23	40.70	3.51	4.15
	DF-2-2	16.78	31.30	1.69	3.16
	JP-8	22.30	28.78	2.34	3.00
1600	DF-2-1	32.13	44.58	3.35	4.62
	DF-2-2	19.78	36.15	2.03	3.71
	JP-8	21.43	29.60	2.29	3.14
1400	DF-2-1	36.95	44.15	3.80	5.06
	DF-2-2	24.13	38.65	2.45	4.40
	JP-8	22.40	35.08	2.35	4.10
1200	DF-2-1	41.23	41.55	4.47	5.02
	DF-2-2	29.60	39.03	3.17	4.70
	JP-8	23.28	36.28	2.56	4.46
			Average	2.83	3.82
			St. Dev	0.89	0.91

Table 15 and 16 show a temperature analysis between the 400 performance runs and 0 hour performance runs for both the JP-8/FT SPK blended fuel engine and the JP-8 fuel engine.

Table 17. JP-8/FT engine energy balance

JP-8/FT SPK Engine								
	JP-8/SPK				JP-8			
Full Load Performance Run @ 2100 RPM	Energy Input [BTU/min]	Energy Output [BTU/min]	Energy Delta [BTU/min]	Fraction Accounted for	Energy Input [BTU/min]	Energy Output [BTU/min]	Energy Delta [BTU/min]	Fraction Accounted for
0 hour	64276	60459	3818	0.941	66441	62809	3632	0.945
100 hour	64993	60461	4531	0.930	66764	62490	4275	0.936
200 hour	61244	58693	2551	0.960	67085	62452	4633	0.931
300 hour	63296	57654	5643	0.911	65960	56038	9921	0.850
400 hour	63359	57624	5735	0.909	66082	59674	6407	0.903
@ 1400 RPM								
0 hour	50013	43719	6294	0.874	51976	44575	7401	0.858
100 hour	50273	46623	3649	0.927	52763	49148	3615	0.932
200 hour	50180	46466	3714	0.926	52248	48538	3711	0.929
300 hour	48098	43162	4935	0.897	51285	41803	9482	0.815
400 hour	48258	44003	4255	0.912	66082	59674	6407	0.903

Table 18. JP-8 engine energy balance

JP-8 Engine - JP-8 Fuel				
	JP-8			
Full Load Performance Run @ 2100 RPM	Energy Input [BTU/min]	Energy Output [BTU/min]	Energy Delta [BTU/min]	Fraction Accounted for
0 hour	64589	50940	13649	0.788
100 hour	55967	52952	3015	0.946
200 hour	63763	56057	7706	0.879
300 hour	63804	56920	6883	0.892
400 hour	63828	55883	7945	0.876
@ 1400 RPM				
0 hour	50927	42799	8129	0.840
100 hour	50479	41412	9068	0.820
200 hour	49989	43416	6574	0.868
300 hour	50186	44050	6136	0.878
400 hour	50436	41749	8688	0.828

$$\dot{m}_f h_f + \dot{m}_a h_a = P_b + \dot{Q}_{cool} + \dot{Q}_{misc} + (\dot{m}_f + \dot{m}_a) h_e$$

$\dot{m}_f = Mass\ flow\ rate\ of\ fuel$ [lb_m/min]
$\dot{m}_a = Mass\ flow\ rate\ of\ air$ [lb_m/min]
$h_f = Enthalpy\ of\ fuel$ [Btu/ lb_m]
$h_a = Enthalpy\ of\ air$ [Btu/ lb_m]
$h_e = Enthalpy\ of\ exhaust\ gas$ [Btu/ lb_m]
$P_b = Brake\ horsepower$ [Btu/min]
$\dot{Q}_{cool} = Energy\ to\ coolant$ [Btu/min]
$\dot{Q}_{misc} = Energy\ not\ measured\ directly$ [Btu/min]

This equation accounts for all of the energy before and after combustion. The input energy is given by the energy contained in the air and fuel, while the energy after combustion is measured by the power output of the engine, the energy transferred to the coolant system, the energy transferred to the exhaust and energy that is not directly accounted for, such as energy of the radiated heat and frictional forces. The mass flow rate of fuel is measured directly using a mass scale, while the mass flow rate of air was measured using a lambda sensor in the engine, which measures the air/fuel ratio. A laminar flow element was attached to the air intake of the engine before every full load performance run, but the flow rate of air did not match those of the lambda sensor. It was discovered that improper calibration was used on the laminar flow element, and the lambda sensor gave a more accurate reading. Enthalpy of intake air and exhaust gasses were taken from an air enthalpy table and treated as a function of temperature only, since both intake and exhaust are near atmospheric pressure. Energy to the coolant is measured from the increase in coolant temperature and coolant flow rate. Frictional forces and radiated heat are difficult to measure directly and are accounted for in the term $\dot{Q}_{misc}$, which accounts for ~7-10% of the total energy at full load.

Table 19. Low estimate energy input for 10 hour cycle

Definition of 10 Hour Cycle					
					Low Estimate Energy Input
Sub-Cycle	% Rated Speed	RPM	% Load	Duration in hrs	[Btu/min]
1	Idle (1)(7)	-	0	0.5	N/A
2	100	2100	100 (5)	2	60000
3	Governed speed (2)	2150	0	0.5	N/A
4	75	1575	100 (5)	1	45000
5	Idle (1)_(3)_100		0(4min)__100(6min)	2	36000
6	60	1260	100	0.5	36000
7	Idle (1)(7)	-	0	0.5	N/A
8	Governed speed (4)	2150	70 (6)	0.5	N/A
9	Max Torque Speed	1400	100 (5)	2	50000
10	60	1260	50 (6)	0.5	N/A
Total				10	Average: 35500 [Btu/min]

Table 19 shows the calculation for a low estimate energy input for a 10 hour cycle, which averages out to 35,500 Btu/min. The unavailable values (represented as N/A) will contribute positively to the energy estimate, but were omitted and treated as 0 to obtain a low estimate. This estimate is used when calculating the effect of additional oil used in the JP-8/FT SPK engine.

Table 20. Data used in energy balance equation for JP-8/FT SPK blended fuel engine

	Engine Speed RPM	Fuel Mass Flow lbm/min	Fuel Enthalpy Btu/lbm	Air Mass Flow lbm/min	Air Enthalpy Btu/lbm	Brake Power Btu/min	Energy Rate to Coolant Btu/min	Exhaust Enthalpy Btu/lbm
JP-8/FT SPK Blend Fuel Engine - 0 Hour Full Load Performance Run								
JP-8	2100	2.90	18616	96.9	128.0	19732	15070	280.7
	1800	2.87	18616	93.9	128.0	19661	15353	287.7
	1600	2.58	18616	89.2	127.9	18059	10966	282.1
	1400	2.24	18616	79.8	128.1	15889	6036	276.0
	1200	1.89	18616	68.9	128.2	13369	6186	273.2
JP-8 FT/SPK	2100	2.78	18745	95.6	127.9	18805	14404	277.0
	1800	2.69	18745	91.7	127.6	18616	11584	281.9
	1600	2.43	18745	85.8	128.1	17062	9269	278.3
	1400	2.14	18745	77.0	128.1	15352	6665	274.3
	1200	1.81	18745	66.5	128.1	12879	7534	272.0
JP-8/FT SPK Blend Fuel Engine - 100 Hour Full Load Performance Run								
JP-8	2100	2.91	18616	98.5	128.2	19412	14377	283.1
	1800	2.89	18616	95.3	128.1	19506	13436	290.0
	1600	2.57	18616	89.6	128.1	18012	11706	284.1
	1400	2.27	18616	82.7	128.1	15959	9625	277.4
	1200	1.92	18616	72.0	128.1	13504	7746	273.7
JP-8 FT/SPK	2100	2.81	18745	96.3	128.4	18743	13892	280.8
	1800	2.75	18745	92.7	128.4	18691	12995	286.5
	1600	2.42	18745	85.9	128.5	17104	11129	281.1
	1400	2.15	18745	78.1	128.5	15287	9192	276.1
	1200	1.83	18745	68.6	128.5	12970	7618	273.0
JP-8/FT SPK Blend Fuel Engine - 200 Hour Full Load Performance Run								
JP-8	2100	2.94	18616	96.9	127.4	19307	14127	290.7
	1800	2.90	18616	93.8	127.5	19266	13330	297.8
	1600	2.64	18616	89.3	127.6	17625	11392	293.5
	1400	2.27	18616	78.3	127.9	15648	9508	290.1
	1200	1.95	18616	67.6	127.8	13324	7693	288.8
JP-8 FT/SPK	2100	2.65	18788	89.0	127.7	18625	13892	285.3
	1800	2.76	18788	91.6	127.6	18543	12618	294.8
	1600	2.48	18788	85.4	127.6	16832	10956	291.1
	1400	2.16	18788	75.6	127.6	14966	9129	287.8
	1200	1.86	18788	65.2	127.5	12785	7437	287.4
JP-8/FT SPK Blend Fuel Engine - 300 Hour Full Load Performance Run								
JP-8	2100	2.90	18616	93.0	128.2	19026	14161	NA
	1800	2.84	18616	89.8	128.2	18975	13269	NA
	1600	2.58	18616	84.1	128.2	17310	11301	NA
	1400	2.24	18616	74.4	128.1	15522	9419	NA
	1200	1.92	18616	63.8	128.1	13175	7716	NA
JP-8 FT/SPK	2100	2.76	18745	89.7	129.1	18010	13655	NA
	1800	2.67	18745	86.0	129.2	17845	12537	NA
	1600	2.38	18745	78.3	129.2	16226	10623	NA
	1400	2.09	18745	69.1	129.3	14544	9034	NA
	1200	1.81	18745	59.9	129.3	12480	7491	NA
JP-8/FT SPK Blend Fuel Engine - 400 Hour Full Load Performance Run								
JP-8	2100	2.92	18616	90.5	129.9	19041	14389	NA
	1800	2.85	18616	87.6	129.9	18896	13240	NA
	1600	2.55	18616	80.6	129.9	17328	11498	NA
	1400	2.25	18616	72.4	129.9	15369	9760	NA
	1200	1.49	18616	45.8	129.9	9863	6132	NA
JP-8 FT/SPK	2100	2.76	18745	90.3	128.3	18063	13414	NA
	1800	2.69	18745	86.6	128.3	17951	12606	NA
	1600	2.41	18745	79.7	128.4	16344	10756	NA
	1400	2.10	18745	69.8	128.4	14614	9199	NA
	1200	1.82	18745	60.2	128.4	12448	7355	NA

*If data was not available due to a faulty thermocouple or insufficient fuel properties data, reasonable values from similar performance tests were used to approximate energy balance.

Table 21. Data used in energy balance equation for JP-8/FT SPK blended fuel engine

	Engine Speed	Fuel Mass Flow	Fuel Enthalpy	Air Mass Flow	Air Enthalpy	Brake Power	Energy Rate to Coolant	Exhaust Enthalpy
	RPM	lbm/min	Btu/lbm	lbm/min	Btu/lbm	Btu/min	Btu/min	Btu/lbm
JP-8 Fuel Engine - 0 Hour Full Load Performance Run								
JP-8	2100	2.82	18659	91.2	130.6	18683	10723	228.9
	1800	2.74	18659	87.2	130.6	18375	18496	233.4
	1600	2.57	18659	82.3	130.7	17209	14977	229.2
	1400	2.22	18659	72.4	130.7	15493	10694	222.5
	1200	1.93	18659	63.4	130.6	13136	8814	215.1
JP-8 Fuel Engine - 100 Hour Full Load Performance Run								
JP-8	2100	2.45	18659	79.1	129.8	18461	16547	NA
	1800	2.70	18659	85.6	129.9	18096	13681	NA
	1600	2.49	18659	79.4	129.9	17019	12398	NA
	1400	2.21	18659	71.1	130.0	15385	10266	NA
	1200	1.90	18659	61.6	130.0	13247	8906	NA
JP-8 Fuel Engine - 200 Hour Full Load Performance Run								
JP-8	2100	2.80	NA	90.6	126.7	18587	14475	246.1
	1800	2.70	NA	84.7	126.8	18257	13349	249.6
	1600	2.47	NA	78.6	126.8	17164	11458	246.6
	1400	2.19	NA	71.4	126.9	15460	10293	240.1
	1200	1.89	NA	62.5	126.8	13319	9963	236.8
JP-8 Fuel Engine - 300 Hour Full Load Performance Run								
JP-8	2100	2.81	NA	88.6	128.0	18549	15409	251.1
	1800	2.71	NA	83.0	128.1	18251	13438	254.2
	1600	2.50	NA	77.3	128.2	17162	11348	251.9
	1400	2.21	NA	70.1	127.9	15504	10800	245.4
	1200	1.89	NA	60.5	127.8	13245	9015	241.6
JP-8 Fuel Engine - 400 Hour Full Load Performance Run								
JP-8	2100	2.81	18659	89.6	126.6	18564	14362	248.5
	1800	2.72	18659	83.8	126.7	18227	12946	251.1
	1600	2.51	18659	77.9	126.7	17092	12145	248.5
	1400	2.22	18659	70.8	126.7	15452	8614	242.3
	1200	1.89	18659	61.3	126.5	13194	14084	238.6
JP-8 FT/SPK	2100	2.63	18745	86.3	126.8	17308	13295	242.8
	1800	2.54	18745	80.0	126.8	17107	11595	245.1
	1600	2.33	18745	73.8	126.9	16050	11133	242.0
	1400	2.08	18745	66.7	126.8	14600	5943	238.6
	1200	1.79	18745	57.2	126.7	12492	8350	236.1

*If data was not available due to a faulty thermocouple or insufficient fuel properties data, reasonable values from similar performance tests were used to approximate energy balance.

VII. Additional Full Load Performance Run Graphs

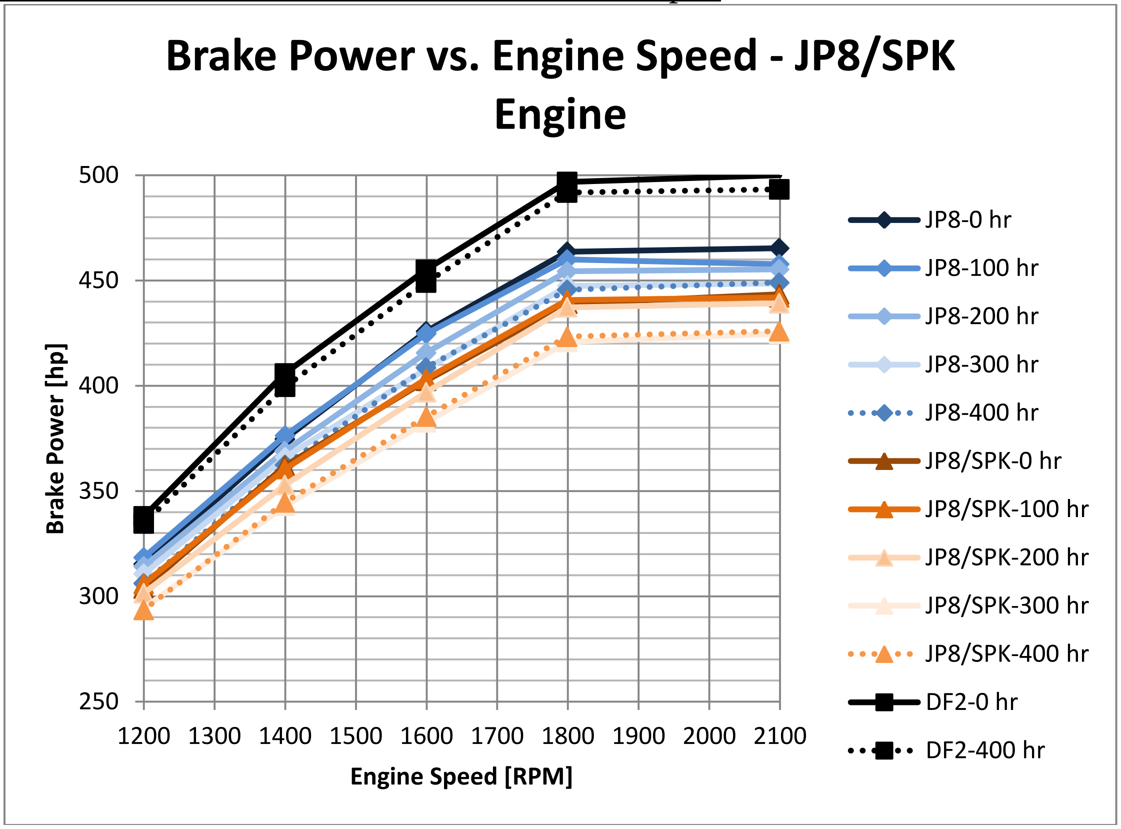

Figure 18. JP-8/SPK engine brake power vs. engine speed of all FLPRs

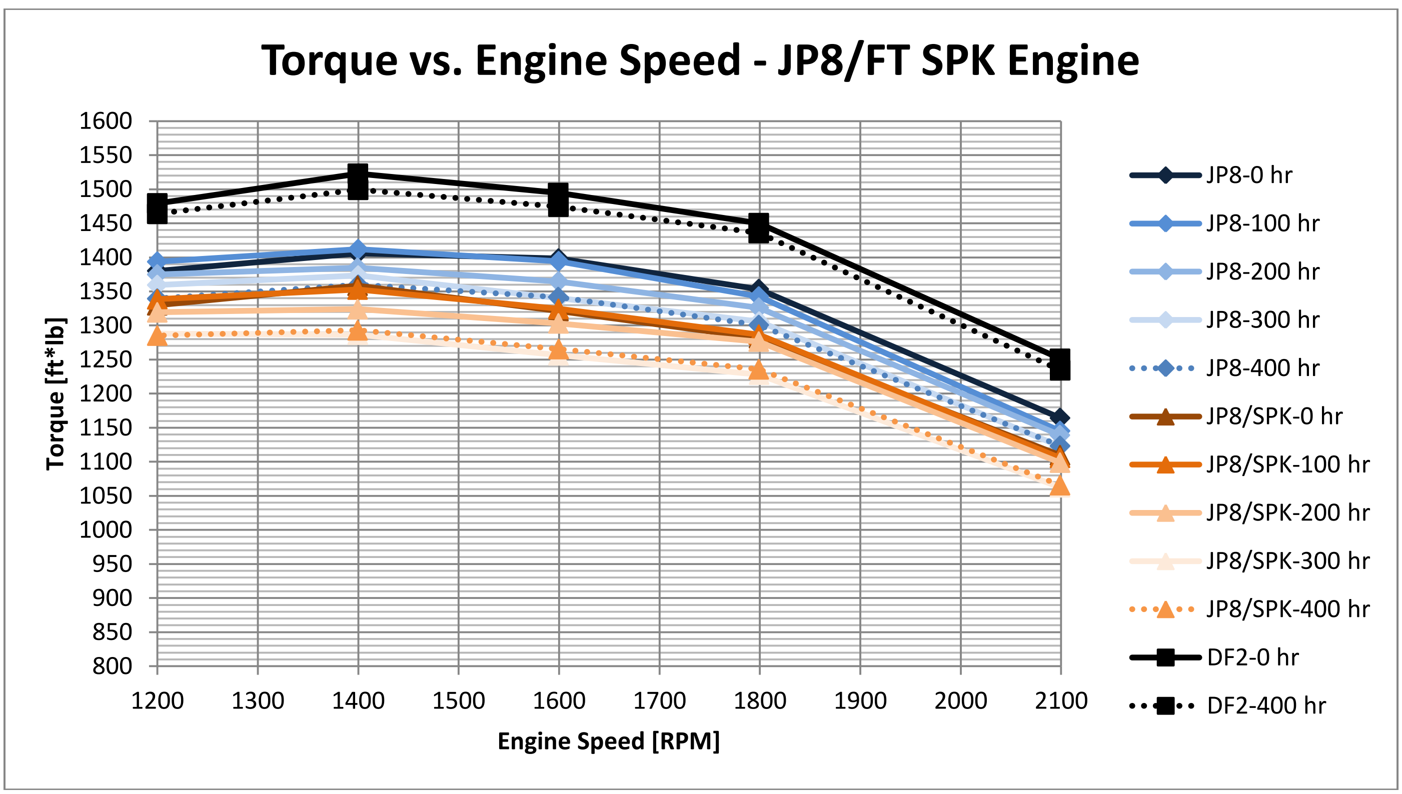

Figure 19. JP-8/SPK engine torque vs. engine speed of all full load performance runs

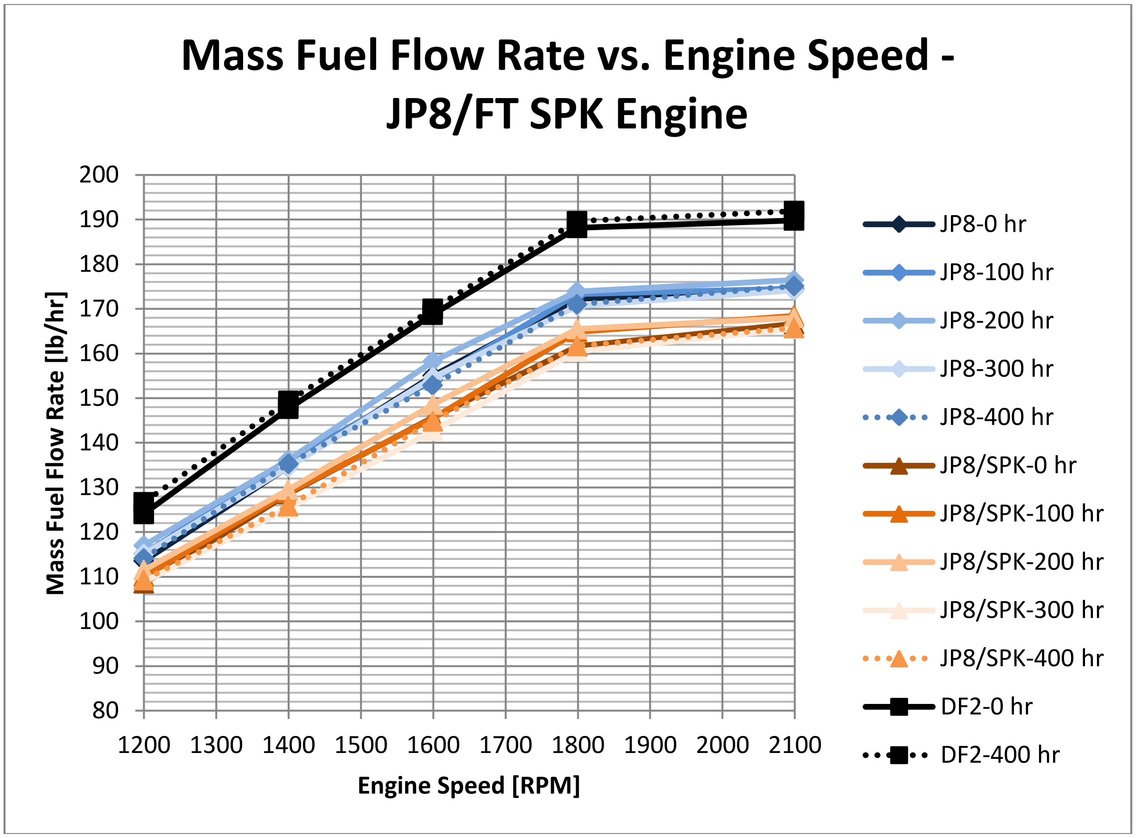

Figure 20. JP-8/SPK engine mass fuel flow rate vs. engine speed of all full load performance runs

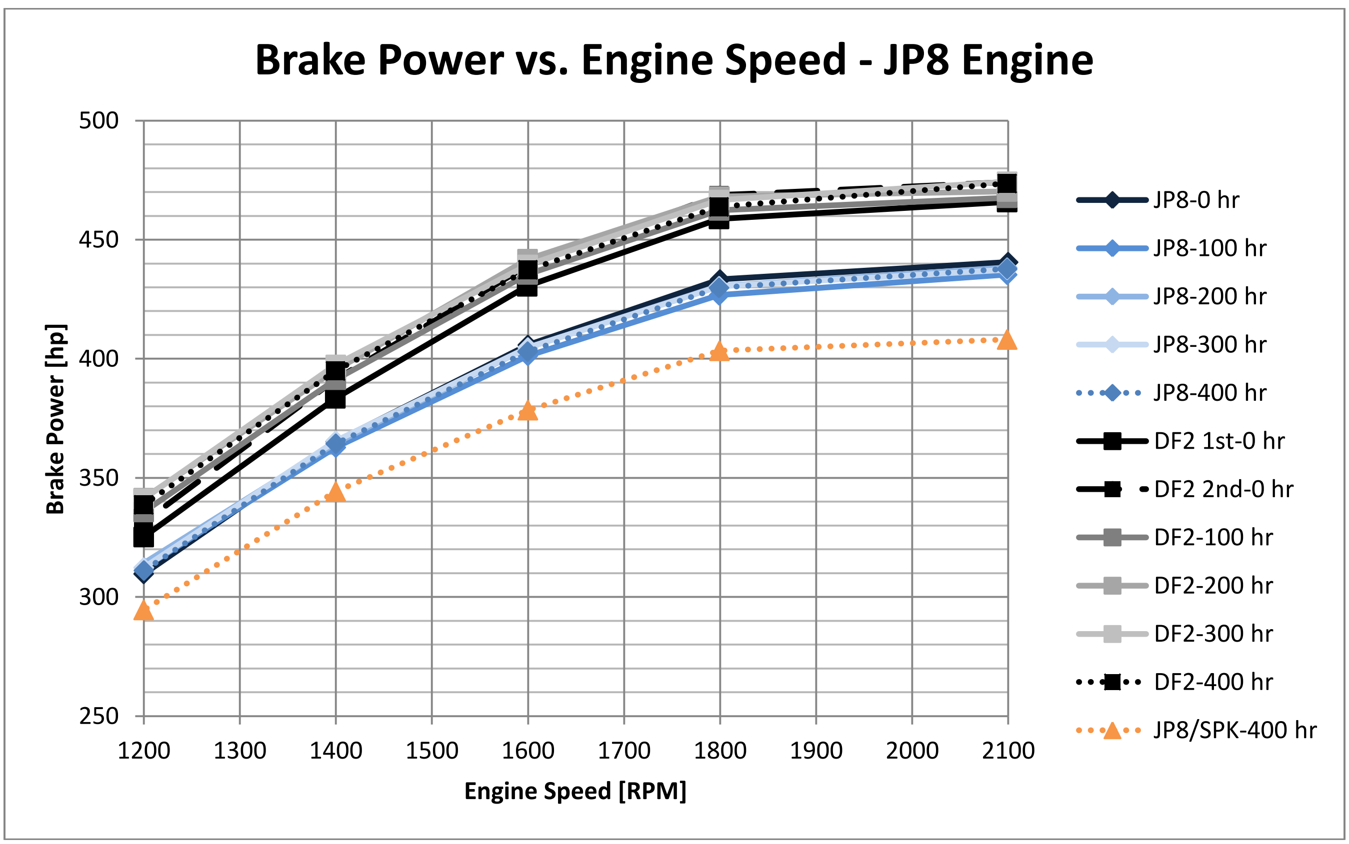

Figure 21. JP-8 engine brake power vs. engine speed of all FLPRs

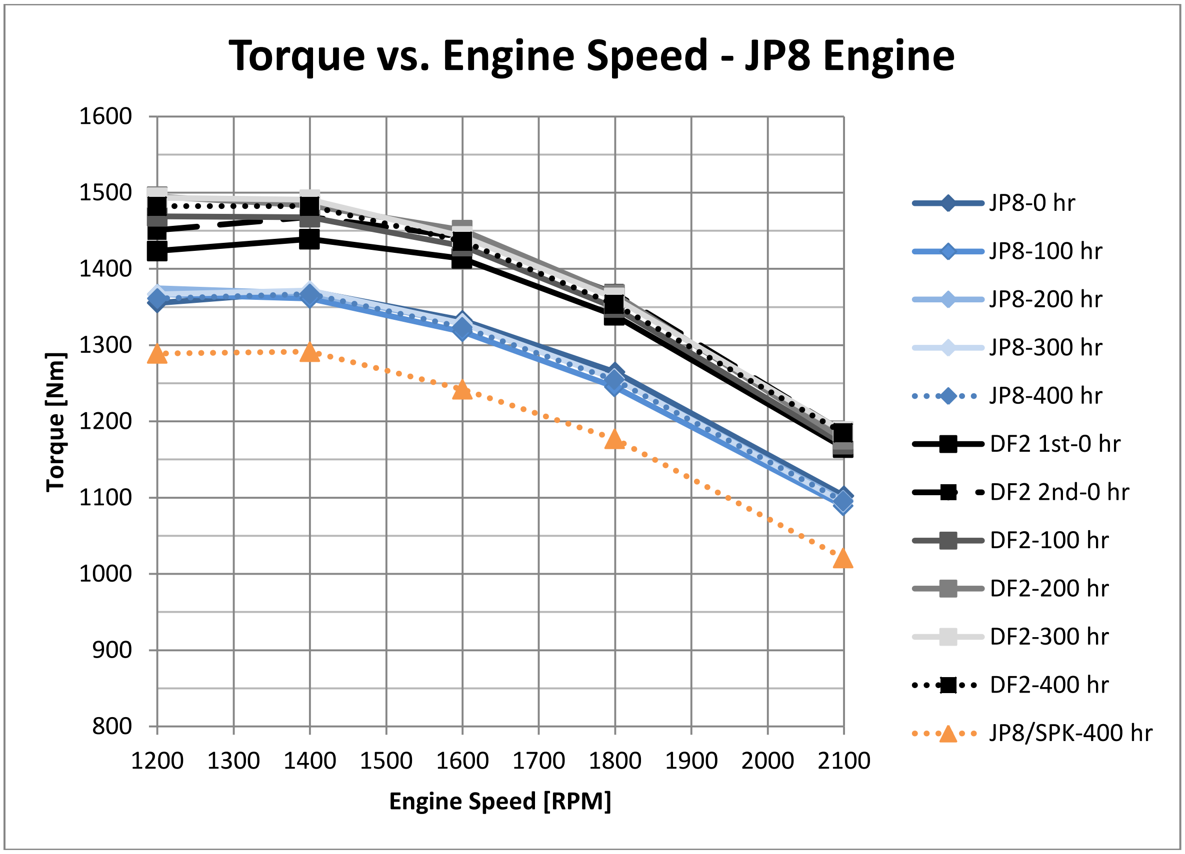

Figure 22. JP-8 Engine torque vs. engine speed of all FLPRs

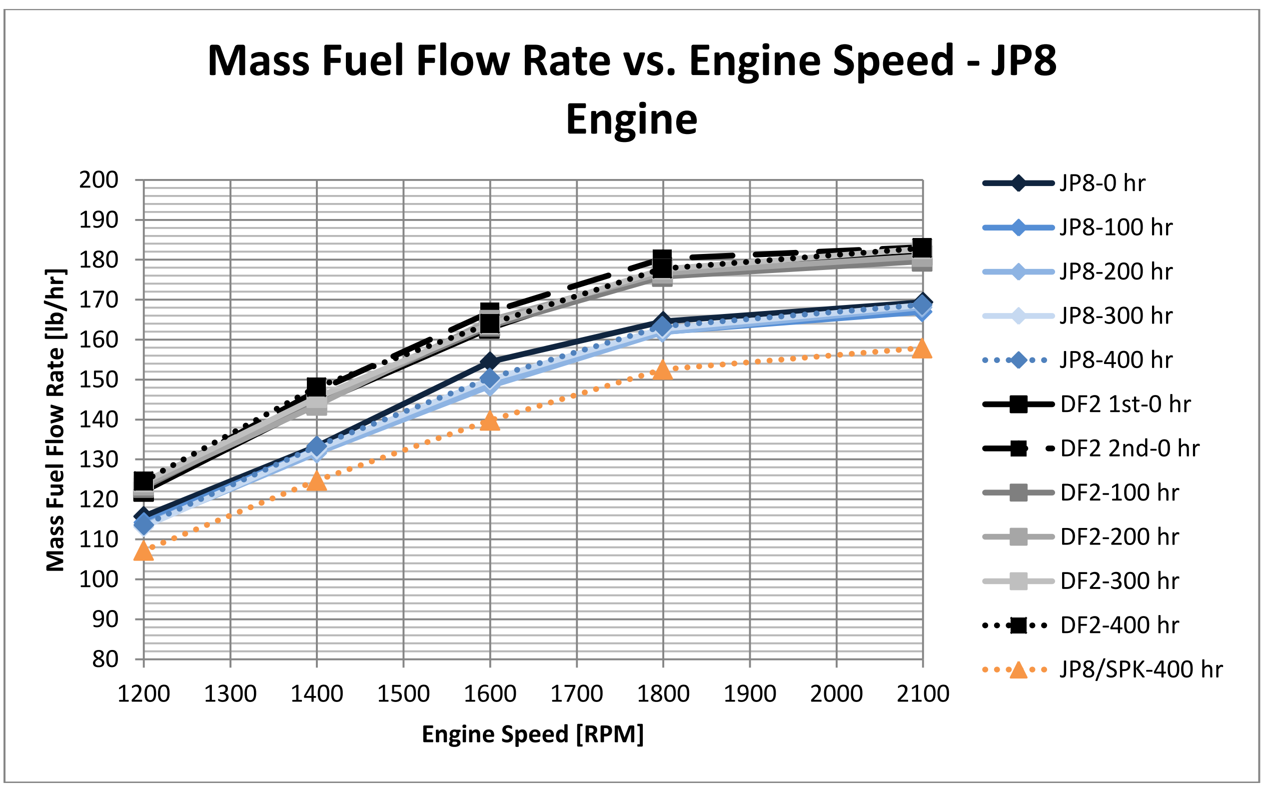

Figure 23. JP-8 engine fuel flow rate vs. engine speed of all FLPRs

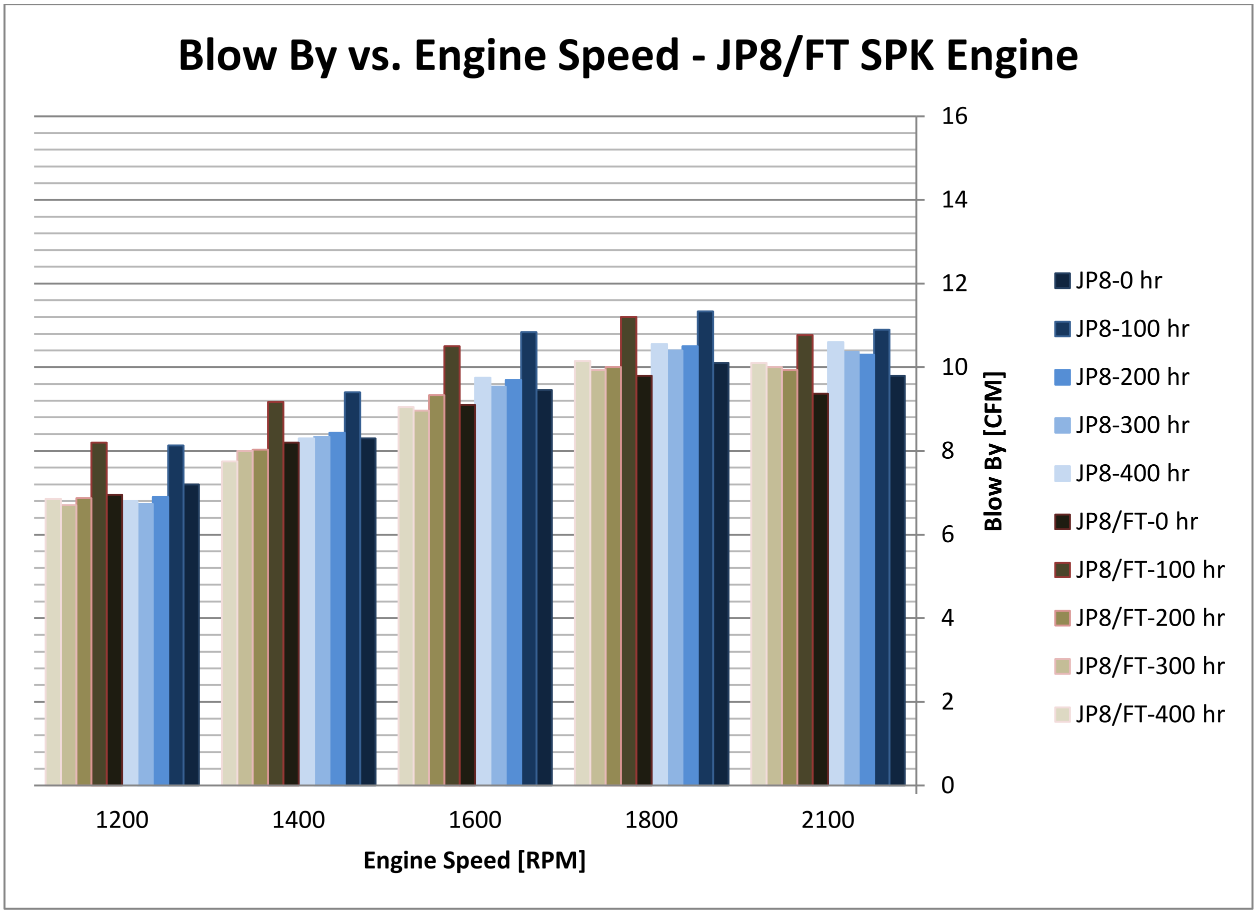

Figure 24. Graph of cylinder blow by in JP/FT SPK Engine

The variance in blow-by in Figures 24 and 25 explain the differences of initial engine brake power of the two engines. Since the JP-8/FT engine has a lower blow-by, it was initially an engine with tighter tolerances after rebuild. The consistency of blow-by through the durability tests support that there were no excess part deteriorations in the cylinders.

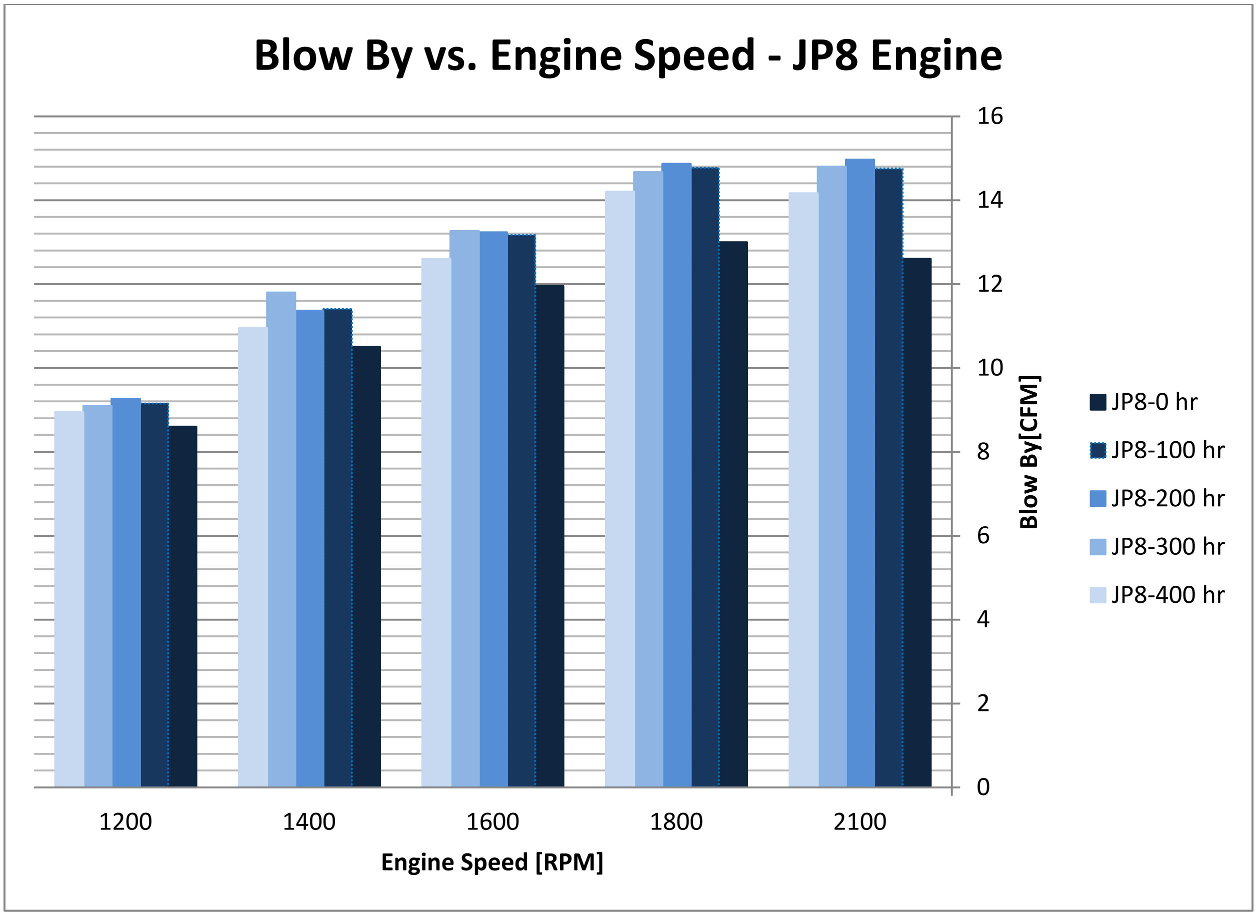

Figure 25. Graph of cylinder blow by in JP-8 engine

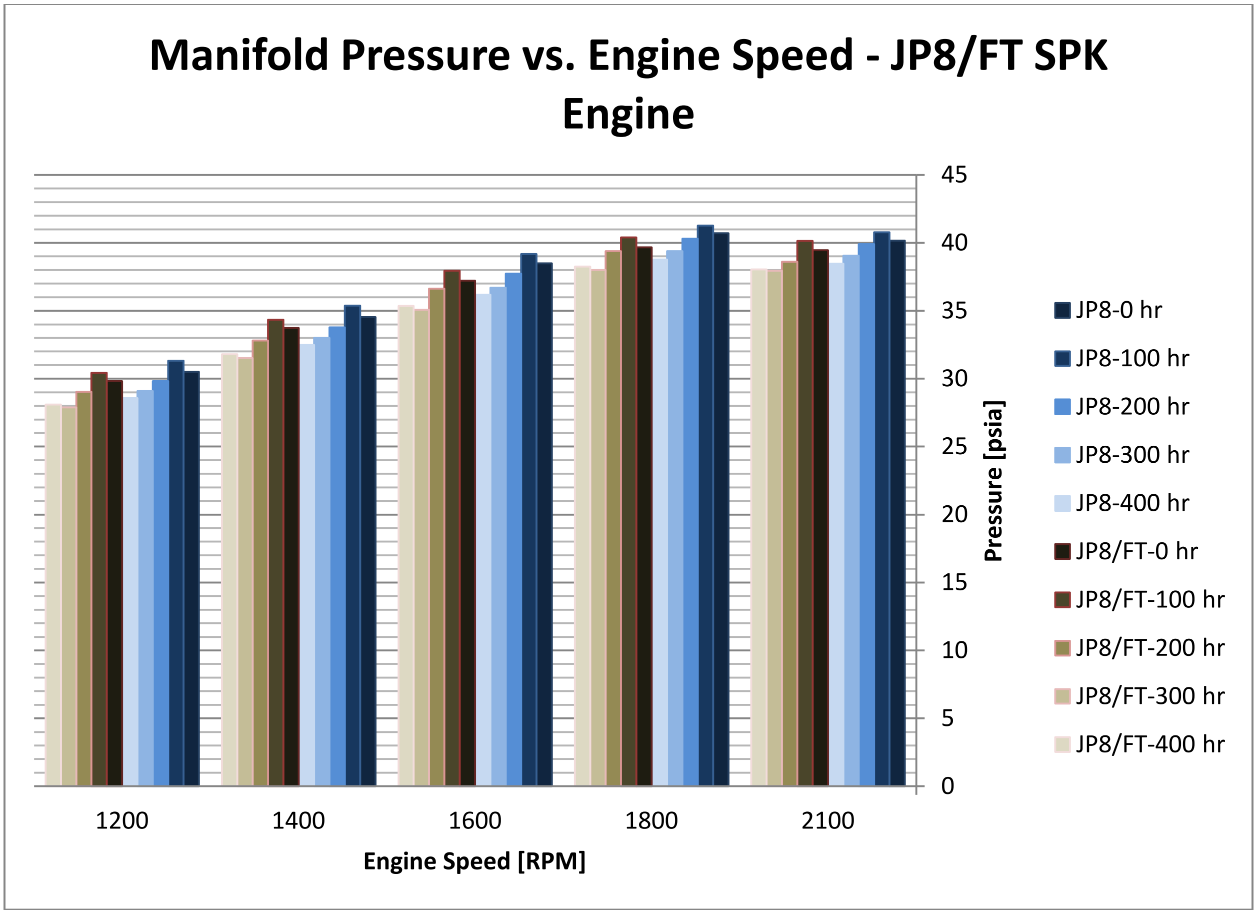

Figure 26. JP-8/FT SPK engine manifold pressure

The turbine end of the turbocharger was damaged after 140 hours of testing for the JP-8/FT SPK engine. This damage was not discovered until the disassembly and the remainder of the 400 hours were run with the damaged turbine. Graphed in Figure 26 are the performance run boost pressures, measured at the air pressure out of the compressor. There is an average decrease of about 2% between the second performance run (100 hours) and third performance run (200 hours) where the damage occurred, which may be the primary cause of the power loss (Figure 18) in this engine.

In the JP-8 engine, the air pressure sensor out of the compressor was damaged and not reading correctly, thus the manifold pressure changes of the two engines cannot be compared.

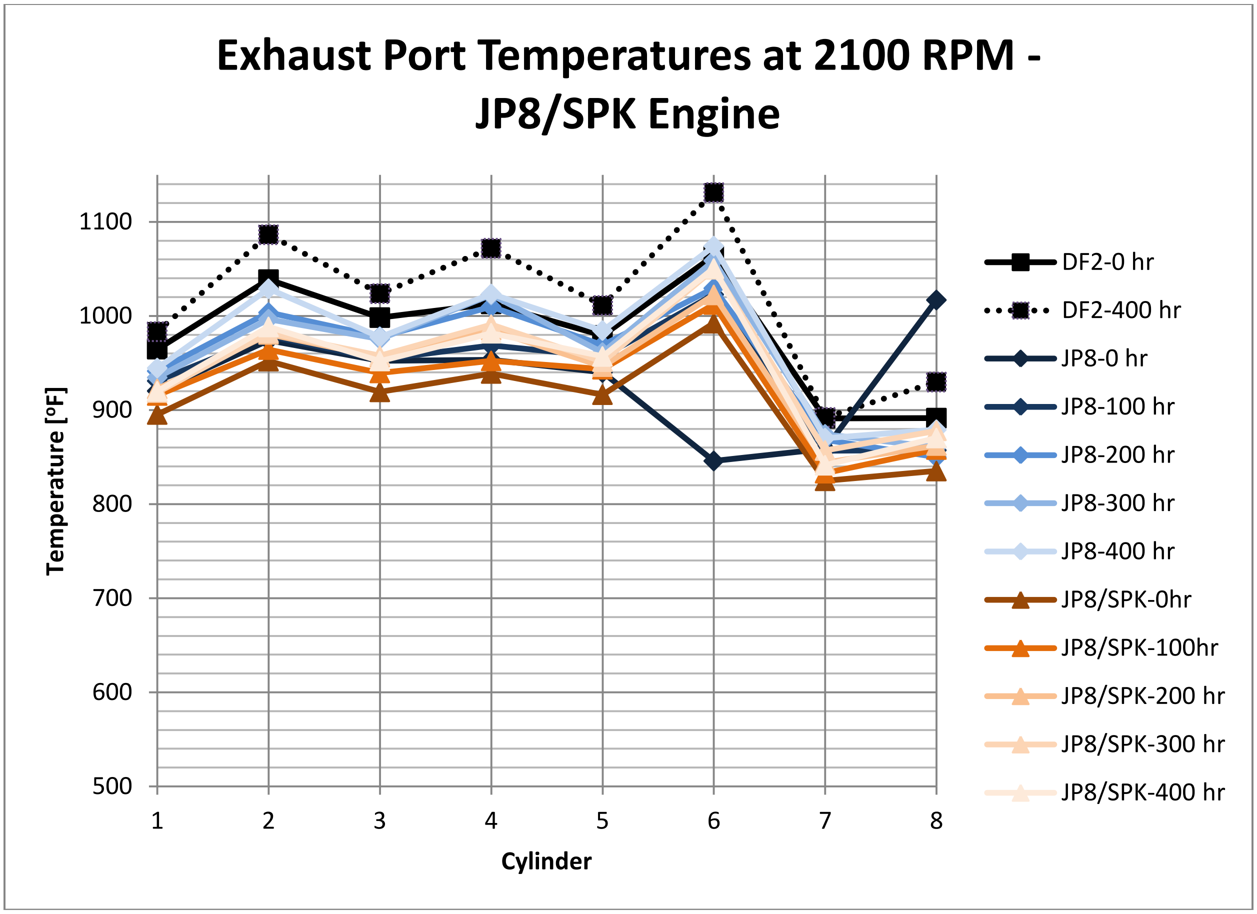

Figure 27. Exhaust port temperatures at full power for the JP-8/SPK engine

The 0 hour JP8 performance run has a cooler than average temperature in cylinder 6 and a larger than average temperature in cylinder 8 for unknown reasons. Plots of the individual cylinder temperatures are shown in Figure 27 and Figure 28. The JP8 performance run was executed after the DF-2 run and before the synthetic fuel blend run, which both followed the temperature trend. Exhaust temperatures before and after the turbocharger were consistent with readings from the thermocouples located in cylinder 6 and 8, which suggests that the instrumentation was reading correctly. There was also not an unexpected change in power or fuel rate at the inconsistent data points.

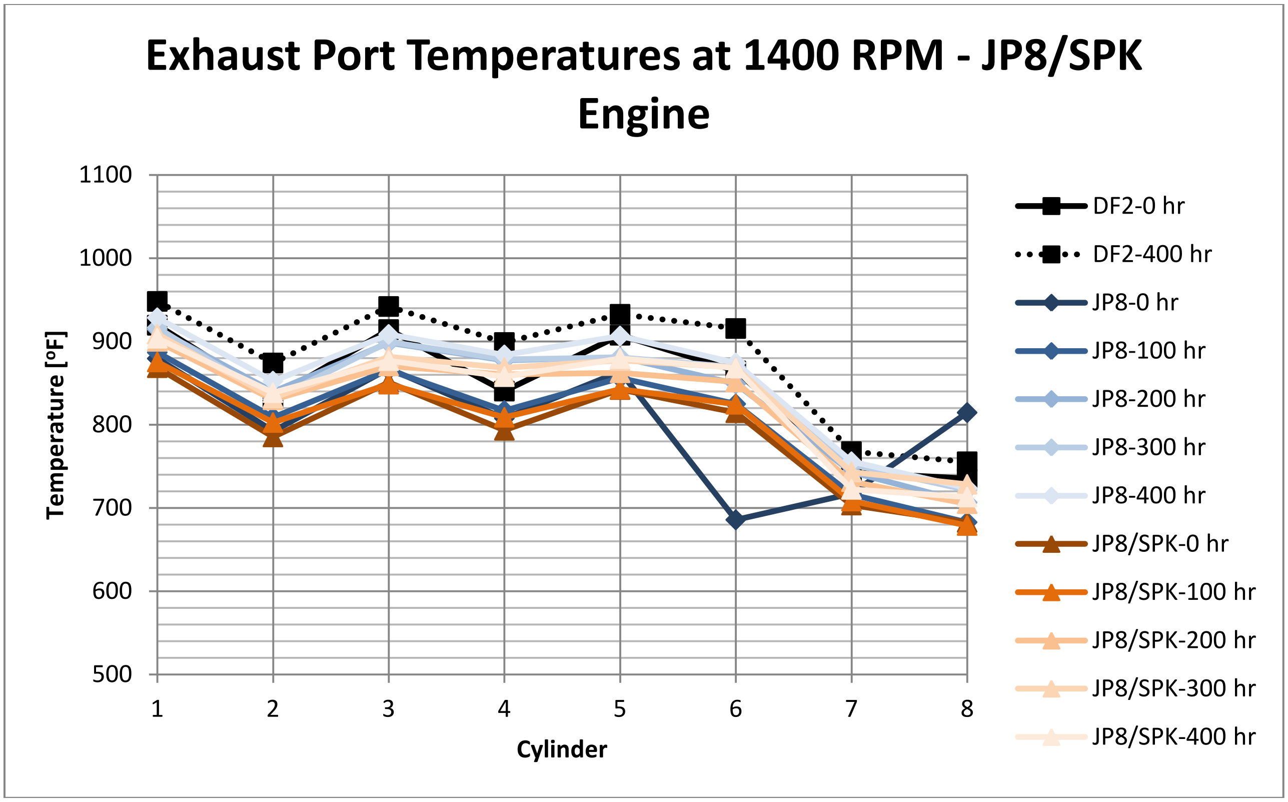

Figure 28. Exhaust port temperatures at max torque for JP-8/SPK engine

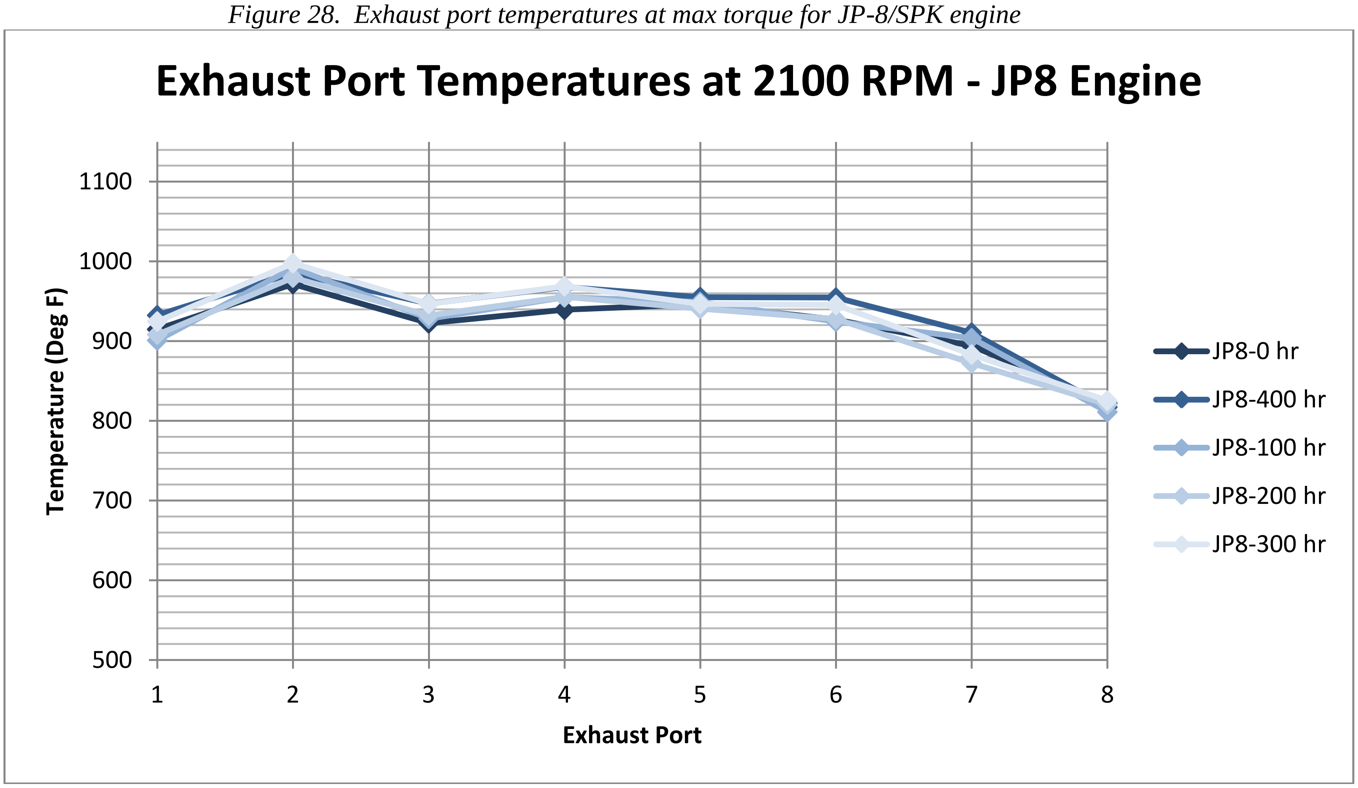

Figure 29. Exhaust port temperatures at full power for the JP-8 engine

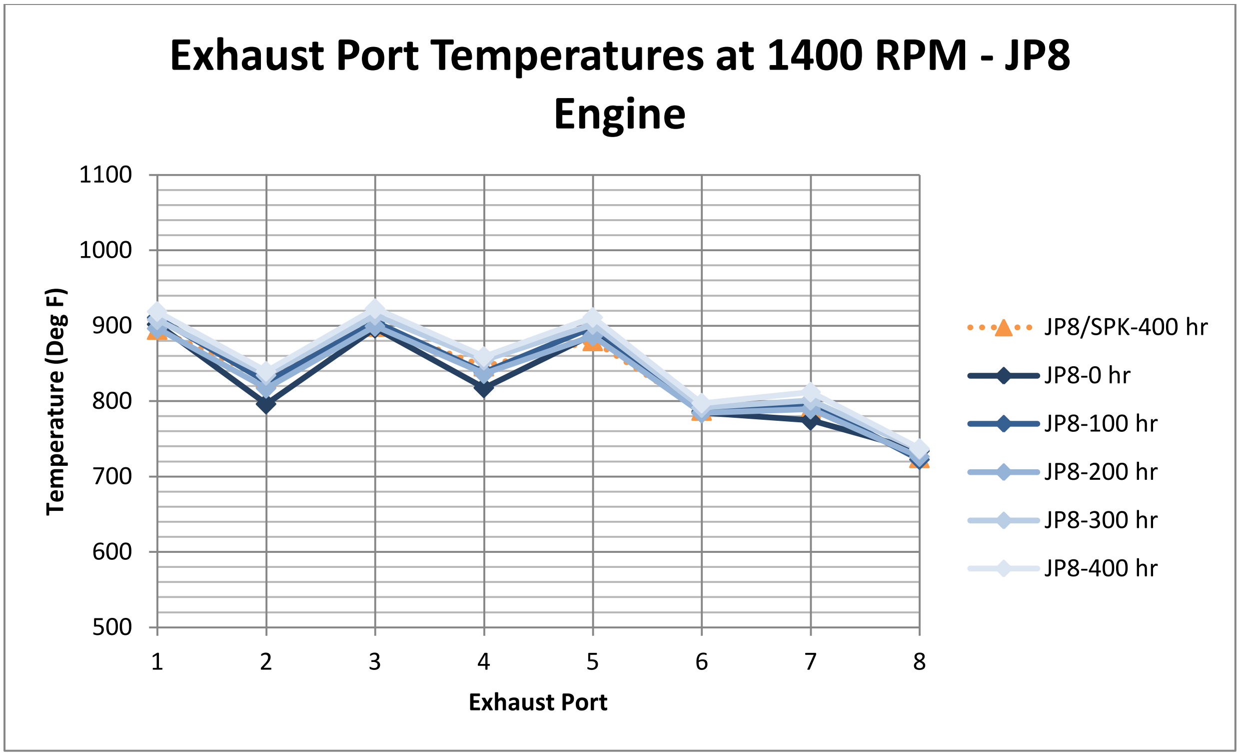

Figure 30. Exhaust port temperatures at max torque for the JP-8 engine

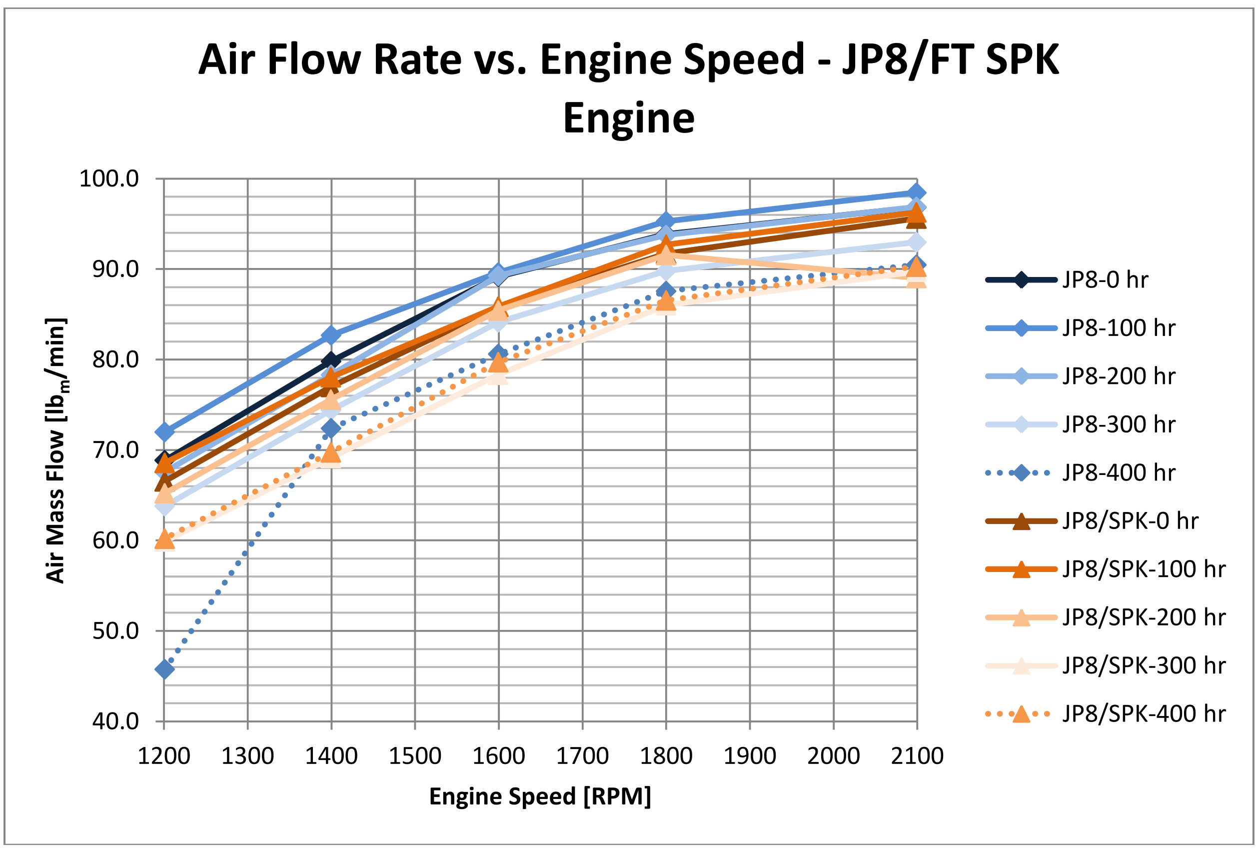

Figure 31. Air flow rate vs. engine speed for full performance runs of JP8/FT SPK engine

The air flow rate was derived from the lambda sensor, since the laminar flow element produced unreliable results.

VIII. Additional Data

Table 22. Scrapings from cylinder head during disassemblies

8V92TA Engine Cylinder Scraping Samples			
Elements		JP8 Engine	JP8 SPK/FT 50/50 Blend Engine
		FL-14092-11 Scrapings from Cylinder Head 4	FL-14095-11 Scrapings from Cylinder Head 1
		Concentration (%)	
Mg	Magnesium	0.094	0.198
Al	Aluminum	0.007	0.000
Si	Silicon	0.097	0.055
P	Phosphorus	3.100	3.830
S	Sulfur	3.360	2.890
K	Potassium	0.010	0.022
Ca	Calcium	14.380	16.540
Cr	Chromium	0.014	0.010
Mn	Manganese	0.010	0.014
Fe	Iron	1.047	0.389
Ni	Nickel	0.007	0.005
Cu	Copper	0.011	0.033
Zn	Zinc	7.389	7.158
Sn	Tin	0.351	0.837
Ba	Barium	0.210	0.000
Pb	Lead	0.120	0.127

Scrapings were taken of the deposits on the cylinder heads of both engines during the engine disassemblies. The metals in the scrapings are indicative of oil additive packages and the sulfur content is most likely from fuel.

References

[1] Army Regulation 70–12, *Fuels and Lubricants Standardization Policy for Equipment Design, Operation, and Logistic Support* 1997.

[2] Frame, E. A., R. A. Alvarez, Matthew G. Blanks, Robert L. Freerks, Leo L. Stavinoha, Patsy A. Muzzell, and Luis Villahermosa. "Alternative Fuels: Assessment of FT Fuel for Military Use in 6.5L Diesel Engine." *Society of Automotive Engineers* Jan. 2004. SAE Paper Number 2004-01-2961.

[3] Muzzell, Patsy A., Brian J McKay, Eric R. Sattler, Leo L. Stavinoha, and Ruben A. Alvarez. "The Effect of Switch-Loading Fuels on Fuel-Wetted Elastomers." *Society of Automotive Engineers* Jan. 2007. SAE Paper Number 2007-01-1453.

[4] McKay, Brian J., Luis A. Villahermosa, and Kathryn S. Kline. "Bench-top Lubricity Evaluator Correlation with Military Rotary Fuel Injection Pump Test Rig." *Society of Automotive Engineers* Jan. 2005. SAE Paper Number 2005-01-3899.

[5] Muzzell, Patsy A., Eric R. Sattler, Angela Terry. "Properties of Fischer-Tropsch (FT) Blends for Use in Military Equipment." *Society of Automotive Engineers* Jan. 2006. SAE Paper Number 2006-01-0702.

[6] SFPE Handbook of Fire Protection Engineering. 3rd Edition, 2002. Page 3-25.